Automated Building Monitoring using a Wireless Sensor Network

Vahid Safar-Nourollah

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_____ Chair
Dr. H. Harutyunyan

_____ Examiner
Dr. J. Opatrny

_____ Examiner
Dr. J. W. Atwood

_____ Supervisor
Dr. Lata Narayanan

Approved by _____
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_____ 20 ____ _____
Dr. Robin A.L. Drew, Dean
Faculty of Engineering and Computer Science

Abstract

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Building monitoring is one of the challenging issues in building construction, due to its high cost and the time consuming procedure for implementation and maintenance. It is also a critical issue that directly affects building security, safety, and management, energy saving, and tenants' convenience. Wireless sensor networking is a new networking technology that holds great promise for monitoring, evaluation and management of buildings. However, sufficient work has not been done in the application part of wireless sensor networks for building monitoring. In this thesis, we show how advanced wireless sensor technology can be used by building managers to monitor climate conditions, brightness level, lamp status and room occupancy in buildings as well as by the wireless sensor network administrator to monitor the nodes' connectivity and conditions in the network. We conceive of the building monitoring application as being divided into three main parts. First, wireless sensor hardware is programmed to process signals from sensors and transmit the data in a suitable format to a gateway/server application using multi-hop routing. The second task involves the forwarding of the signals sent by the wireless sensor nodes to the end user application by the gateway/server application. The gateway/server also archives the sensor data in a database for

further retrieval and analysis. The third part consists of an end user application for processing the sensor data sent by the wireless sensor nodes and then forwarded by the gateway/server. The end user application visualizes the network topology, network connectivity graph and real time information of individual motes. In addition, this application provides the real time analysis of the data and functionalities for search and observation. Finally, the end user application allows users to analyze the rooms and network conditions by mining the database using different parameters such as the type of data and the time of data acquisition. The system and related analysis were applied on a real case study — the eighth and ninth floors of the Engineering and Visual Arts building of Concordia University.

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Chapter 1

Introduction

A Wireless Sensor Network (WSN) consists of spatially distributed autonomous devices (motes) using sensors in order to cooperatively sense physical or environmental conditions, such as temperature, vibration, pressure or pollutants at different locations. The motes send raw or processed data using their radio transceiver to the base (sink) node(s) using multi-hop communications [29, 67]. The base nodes are one or more distinguished components of the wireless sensor network with more computational, energy and communication resources. They act as a gateway between sensor nodes and the end user. Sensor nodes can be considered as small computers, extremely basic in terms of their interfaces and their components. They consist of a processing unit with limited computational power and limited memory, sensors (including specific conditioning circuitry), a communication device (usually radio transceivers or alternatively optical), and a power source mostly

in the form of battery. Other possible inclusions are energy harvesting modules, and secondary communication devices (e.g., USB).

The basic premise of a wireless sensor network is to perform networked sensing using a large number of relatively unsophisticated sensors, instead of the conventional approach of deploying a few expensive and sophisticated sensing modules. The potential advantage of networked sensing over the conventional approach, can be summarized as greater coverage, accuracy and reliability at a possibly lower cost. Some of the early works on wireless sensor network [14, 18, 19] motivate and discuss these benefits in detail. In other words, wireless sensor networks include the ability to withstand harsh environmental conditions, ability to cope with node failures, have dynamic network topology, be able to have large scale of deployment with unattended operation, ease of installation, time awareness for coordination with other nodes and self-diagnosis reliability. However, these networks have their own unique constraints and challenges, which include limited power, limited network communication bandwidth and limited memory [94].

The development of wireless sensor networks was originally motivated by military applications such as battlefield surveillance. However, wireless sensor networks are now under development for further usage in many civilian application areas, including environment and habitat monitoring, health care applications, home automation, and traffic control [28, 67]. In a typical application, a wireless sensor network is scattered in a region to collect data through its sensor nodes.

Area monitoring is one of the common applications of wireless sensor networks. In area monitoring, the wireless sensor network is deployed over a region where some specific phenomena or several area conditions should be monitored. When the defined event or the real time condition of the area (heat, pressure, sound, light, electro-magnetic field, vibration, etc.) is detected by the sensors, the raw or processed data is reported to one of the base stations in order to take appropriate action (e.g., send a message on the Internet or to a satellite). Depending on the exact application, different functions require different data-propagation strategies, based on the needs for real-time response, redundancy of the data, security, etc.

Building monitoring is one of the challenging issues for building constructors in terms of its high cost and time consuming procedure for implementation and maintenance. Building monitoring is also one of the most critical issues in building operation, in that directly affects building security, safety, energy saving, management and tenants' convenience. Beside the obvious discomfort associated with variation in internal environmental conditions for building tenants, there are real economic costs as reflected in lost productivity and wasted energy due to poorly moderated building climates. Wireless sensor networking is a new networking technology that holds great promises for evaluation and management of building climates [47]. In addition, the existing wireless sensor network applications are not sufficient to satisfy the above mentioned requirements for building monitoring [6]. Thus, we need to develop and deploy a wireless sensor network system that is able

to provide security, safety, energy saving, management and tenants' convenience in buildings.

This thesis aims to introduce a new wireless sensor network system, which is able to monitor building climate and room occupancy, to be used instead of existing building monitoring systems while providing better building safety, energy saving, management and tenants' convenience with lower cost and time for implementation and maintenance. In this thesis, we have investigated the possibility of how a wireless sensor network can meet such needs and bring the new generation of network technology in this area of industry. The research in this study is conducted through real wireless sensor network modeling and testing of the building monitoring system application for monitoring, visualization and analysis of the climate conditions and room occupancy.

1.1 Motivation

Building monitoring systems exist in most of the commercial buildings with the first duty of providing convenience and safety. However, implementation and maintenance of wired systems are time consuming, error-prone and costly (e.g., for existing construction: 2.2$ per linear foot and for new construction: 0.67$ per linear foot [6]). Another issue is when some crisis happens for a building, such as earthquake or fire. Since the damage to the construction make the backbone system fail, the whole system stops operating.

The new technology of wireless sensor network has brought a new level of building monitoring systems by saving the cost and time of implementation and maintenance, providing more safety and robustness and making these systems more stable in hazardous circumstances [47, 57]. The stability of these systems in hazardous circumstances is due to the nature of wireless sensor network, in that each mote in the network is independent of the other motes, they are battery powered, small in size with attached sensors. Also, two other important features that make these systems stable are communication by radio and formation of a mesh network.

In a mesh network, each mote finds the best way through its neighbor motes to the sink. In case of failure of intermediate mote(s) to the sink, data will be redirected by other routes to the sink. Thus, in this situation, the whole network can always operate without any failure related to the lack of functionality of some motes. Moreover, the system is capable of adjusting to any building structure. It is important to mention that with a wired backbone system, we cannot apply major modifications or renovations to the system without costly and time consuming procedures. However, with a wireless sensor network, both the cost and the time to accommodate various modifications such as renew, add, remove, rearrange and replace sensor nodes, is lower. For instance, in case of upgrading or renewing an old building monitoring system of a hospital, the following tasks should be done: shutting down all systems, changing the cables and wiring by going through the

walls and taking out the old sensors, replacing them with new ones. However, for renewal of such systems by wireless sensor network, all these mentioned tasks can be done by placing the motes in the needed places.

Nowadays, the average cost of each mote is about 100 CAD but it is predicted by Intel and Cnet companies that each of them will cost few cents in the near future [37, 57]. In addition, source code of the motes is developed in open source programming language and operating system such as NesC and TinyOS [56, 60]. As a result, wireless sensor applications can have the following advantages: availability of the source code with the right to modify it by enabling the unlimited tuning and improvement of a software product and the right to redistribute modifications and improvements to the code for more reusability.

We summarize below the advantages of wireless sensor networks for building monitoring applications:

- Simple, more flexible system design
- Faster and easier installations
- Smoother and less costly migration staged to accommodate budgets and schedules
- More stability in hazardous circumstances
- Less cost and fewer constraints associated with maintenance
- Open source, more applicable to modification and improvement

During the last decade, there have been several research projects that have led to some improvements in different areas (subfields) of wireless sensor networks such as routing algorithms, MAC layer protocols, localization algorithms, data gathering, hardware modules, radio transceivers etc. However, there has not been enough focus on the application layer of this technology in building monitoring.

Despite the importance of wireless sensor networks in building monitoring [47], the only major work in this field so far was done by Siemens [77] and UC Berkeley [87, 86, 21]. Teams at UC Berkeley have addressed mobile agents' localization in the building for find-and-rescue missions, controlling indoor temperature by airflow measurement and controlling systems for producing temperature gradients indoors to study energy implications of using sensor network. Siemens, which is working in the building monitoring field more than any other research group, has recently focused on using wireless sensor network to monitor the temperature of the building only. More related work will be discussed in detail in Chapter 2.

As a summary, we can conclude that sufficient work has not been done in the application part of wireless sensor network for building monitoring, despite the promise of providing security, safety, accuracy, expandability and flexibility in building monitoring.

1.2 Problem definition

The objectives of this thesis are to demonstrate the feasibility of implementing a building monitoring system using a wireless sensor network, to understand the involved challenges and to understand the extent and limitation of information that can be obtained with such an approach.

A building monitoring system using a wireless sensor network clearly consists of at least three parts — the end user application, the sensor network, and the gateway/server to enable communication between the two. Each of the three needs to perform a different set of functions. The requirements and specifications for these three parts are described in the remainder of this section.

1.2.1 End user application

The end user application should satisfy different needs from two main categories of building monitoring system users and beneficiaries: network administrator and building manager. For this purpose, the application should have different features as follows:

Visualization The network administrator should be able to see the connectivity graph of the wireless sensor network, the whole network overview and status, real time status of each mote (current power, remaining life time), real time status of each mote's connectivity (current parent and two alternative parents), floor

plan of building with indication of location of each mote, total number of received messages and lost messages of each mote, etc. However, the building manager, would be interested in having the real time status of each room's climate such as temperature and humidity, brightness and room occupancy.

Alerting For safety reasons, almost all users would like to be alerted in case of any sudden change in the climate conditions of the building such as a sudden temperature drop or rise. The process of alerting can be performed by informing building manager first and then getting delegated to other users.

System overview and search The network administrator and building manager should have an observation of the system overview based on real time data received from the motes. In addition, they would be interested in having the ability to search over the overview for all motes or rooms with some specific criteria. They may be interested in finding rooms based on occupancy for different purposes such as finding conference rooms which are empty or figuring out if a person is in room.

Real time charting The network administrator would be interested in the charting of real time mote's status and network connectivity over time to ensure about the network functionality. However, the building manager would like to have the overview of rooms climate conditions, brightness and room occupancy over the time.

Analysis The network administrator is concerned about the analysis of the data to evaluate the functionality of the network over time in order to inspect and fix different problems such as high ratio of messages lost, low connectivity, high power drop, etc., in individual or set of motes. Also the building manager is interested in studying the climate in rooms over time in order to inspect and evaluate building equipment functionality such as heating and ventilation systems. He would be concerned about the analysis of the occupancy statistics of various rooms to assess the proper usage of the building spaces over time. The building manager would also be interested in studying the lamp status of rooms in different periods of time to explore the proper usage of energy. Finally, both network administrator and building manager are interested in having the ability to query the database to extract all distinct dates and times in which the temperature, humidity or brightness of different rooms have been requested.

Remote connection The users need to connect to the gateway/server remotely from their offices. Therefore, in order to receive messages from the wireless sensor network, the end user application should connect to the gateway/server over the Internet. The connection has to be reliable and connection-based. The end user application should also be able to extract the messages from the packets and queue them for interpretation.

Message interpretation In the end user application, the user wants to have the sensor readings to be categorized and understandable in metric units. Each message received from the motes is a set of bytes that consists of different types of data, which includes sensor readings, network connectivity status, mote's current power, etc., in specific formats. The end user application has to distinguish all distinct data from each message and calculate them in metric units. The data extracted from the messages should be interpreted for different purposes such as visualization, real time scaling, alerting, analysis, etc.

1.2.2 Wireless sensor network

The wireless sensor network should provide the necessary data for the end user application to fulfill its requirements. In addition, the classification of the system that we would plan to design is data gathering and reporting (discussed in detail in Section 2.1.2). For the wireless sensor network, specific requirements should be met as follows:

Quality of service The system should be reliable and robust, implying that the motes should deliver the data to the end user with the most ratio of success (the least ratio of lost messages) accurately. In addition, data should be delivered real time (within a certain period of time from the moment it is sensed), otherwise the data will be useless, since the sensed data in our application is critical toward the safety of building tenants in cases such as sudden temperature drop or rise.

Multi-hop communication Our wireless sensor network needs to have mesh network formation. Data have to be successfully sent to the base station from the farthest motes in the sensor network over the multi-hop communication.

Lifetime of the network Also, this wireless sensor network should last long, meaning that the motes that are battery powered and have limited energy source have to be able to minimize the usage of their radio transceiver, beside having minimum in mote data processing. For addressing the mentioned purpose (energy conservation), the two following factors should be considered: first, synchronization between motes to use the minimum necessary duty cycle of radio transceiver and second, using power-saving algorithms for the radio and balancing the trade off between communication versus computation. While considering the energy saving issue, the system should still remain reliable and robust.

Sensing function Beside monitoring the building climate and brightness level of the rooms, we are interested in monitoring the room occupancy, which is the interest of many building monitoring systems. We would like to calculate the room occupancy based on the readings of light sensors, since it avoids the use of external sensors such as motion detectors. This way, we provide more energy conservation, less and cheaper hardware usage and faster hardware installation.

Network monitoring function Finally, the system should provide information about the status of the network connectivity and mote power. This information

can be used by the network administrator in order to have a detailed view of the network.

1.2.3 Gateway/server

We need a gateway/server between wireless sensor network and end user application. The gateway/server needs to run over a workstation connected to the sink of the wireless sensor network and the Internet at the same time. In addition, the mote data need to be archived in the database as well.

Sink connection The gateway should communicate in a synchronized way to the sink through a port (usually USB) that connects the sink to the workstation. The gateway and sink connection has to be implemented based on the sink hardware and the type of used port. The implementation should be in such a way that makes them synchronized and let the gateway recognize the data baud rate (data transition speed) in order to distinguish distinct messages.

Internet connection It has to serve as a server for listening to any client and forward the messages from sink to the client over the Internet. The gateway to client connection has to be reliable and connection-based over the Internet.

Archiving The users need to have the data to be saved for later access and analysis. Therefore, all data that is received from the motes is required to be stored for further retrieval and analysis. The performance issue arises due to large

scale and short time interval of the received data. In order to address this issue, we need to use a relational database management system to control the performance.

In addition to the above mentioned functional requirements of the end user application, wireless sensor network and gateway, some non-functional requirements should be considered to improve the quality of the system. These requirements can include evolution and quality attributes such as reusability, extensibility and scalability.

1.3 Contributions

In this thesis, we have proposed a system architecture for automated building monitoring systems using a wireless sensor network for monitoring climate, brightness and lamp status of the rooms in a building. We have implemented this system which includes three sub systems, wireless sensor network, gateway/server, and end user application.

The wireless sensor network reports the collected data for temperature, humidity and brightness and the calculated lamp status (room occupancy) to the sink while considering energy conservation by using a low power duty cycle. In the wireless sensor network subsystem, we have deployed a simple new routing algorithm which results from refining and combining two existing routing algorithms. In addition, a new approach has been proposed for detecting lamp status by using light sensors only. The lamp status of a room is an approximation of

the room occupancy. The routing algorithm was implemented to work on top of the Sensornet Protocol [63] and in conjunction with the NetSync component [53] for synchronization of the low power duty cycle. Necessary adjustments to the NetSync component were also made.

The gateway/server forwards the received data from the sink to the end user application that is connected to it. In addition, the gateway/server archives the received data in a database for later retrieval and analysis.

The end user application visualizes the network connectivity. It provides tools to view and search a mote's information. It also provides charts for analyzing the information based on the received data for two categories of the users which are building manager and network administrator. The application interprets the data from the database in order to analyze the building climate, room occupancy and brightness, and functionality of the heating, cooling and ventilation system of the building.

The wireless sensor network has been developed in the NesC programming language and Tinyos operating system. The gateway/server and end user application have been designed in UML and implemented using an object oriented approach in Java. The three main subsystems have been implemented and documented to be reusable and extensible for future improvements.

We have implemented all of the components of all three subsystems for the

purpose of this thesis except two components in our wireless sensor network application; NetSync for synchronization and SPC (Sensornet Protocol) for making multiple network protocols work on the same MAC layer.

The system has been tested by applying it on a real case study and the collected data has been analyzed and discussed in this dissertation.

1.4 Organization of dissertation

The rest of this dissertation is organized as follows: In Chapter 2, we provide some necessary background on wireless sensor network applications, hardware platforms and routing algorithms. The methodology of designing and developing the building monitoring system using a wireless sensor network in order to address the problem defined in Section 1.2 is explained in Chapter 3. In Chapter 4, we validate our system by analyzing the system robustness and correctness along with network reliability and life time. As well, we outline the analysis of collected data. Finally, we list conclusions and recommendations for further work in Chapter 5.

Chapter 2

Literature survey

In this chapter, we provide the necessary background on wireless sensor network applications, hardware platforms, algorithms and protocols that are within the scope of this research.

2.1 Wireless sensor network applications

The range of potential applications that wireless sensor network are envisaged to support is tremendous, encompassing military, civilian, environmental and commercial areas [4]. Wireless sensor network applications typically are involved in monitoring, tracking, and controlling. These applications can be categorized by their objectives, types of measured information, traffic characteristics, data delivery requirements and the way their design space is presented for deployment, etc.

First, we describe different areas of major wireless sensor network applications. Then, we explain different approaches that have been used for building monitoring applications. We describe a classification of wireless sensor network applications and finally, we explain the design issues involved in building monitoring applications.

2.1.1 Areas

The areas in which major wireless sensor network applications have been developed or are under development and research can be categorized as follows [94]:

- Environmental monitoring
- Health care
- Industrial
- Security and surveillance
- Military
- Building monitoring and controlling

For each area, we explain how wireless sensor network can be used. In addition, we mention major works that have been done so far in each case.

Environmental monitoring

In this area, sensors can be used to monitor conditions and movements of wild animals or plants in wildlife habitats. They can also monitor air quality and track environmental pollutants, wildfires, or other natural or man-made disasters. Additionally, sensors can be used to monitor biological or chemical hazards to provide early warnings for disasters such as earthquakes. In fact, in comparison with other areas, environmental monitoring has the most developed applications of sensor networks. Some examples of wireless sensor network applications in this field are: an application to monitor volcanic eruptions with low-frequency acoustic sensors developed by researchers at Harvard University and University of North California [85]; a project with the aim of monitoring glacier behavior via different sensors and linking them together into an intelligent web of resources [64]; a reactive, event driven network for environmental monitoring of soil moisture [13]; a deployed network consisting of 32 nodes on a small island off the coast of Maine, streaming useful live data onto the web (Great Duck Island application) [81]; and in the Mediterranean area, using wireless sensor network for monitoring wildfire events [7].

Health care

Care for the elderly can greatly benefit from sensors that monitor vital signs of patients and are remotely connected to doctors' offices. These applications can

include monitoring of human physiological data, tracking and monitoring of doctors and patients inside an hospital, and drug administration in hospitals [71, 80]. Sensors instrumented in homes can also alert doctors when a patient's situation becomes an emergency or he/she becomes physically incapacitated and requires immediate medical attention. In addition, wireless sensor networks can be used to optimize the health care system in hospitals. For instance, supporting the health care workers in the night shift in which many patients have to be managed by drastically reduced staff [17].

Industrial

Wireless sensors can be used to monitor manufacturing processes or the conditions of industrial equipment. Chemical plants or oil refineries may have miles of pipelines that can be effectively instrumented and monitored using wireless sensor networks. Using smart sensors, the condition of equipment in the field and factories can be monitored to alert for imminent failures. Sensors can also monitor and track assets for industries such as trucks or other equipment, especially in an area without a fixed networking infrastructure. These tracking sensors can vary from GPS-equipped locators to passive RFID (Radio Frequency IDentifiers) tags. In this area, RFID tags are the most far-reaching wireless technology [34], which are being used in many fields. For instance, Airbus A380 airplane is equipped with about 10,000 RFID chips. The plane has passive RFID chips on removable parts

such as passenger seats and plane components for faster asset management and maintenance [2].

Security and surveillance

An important application of sensor networks is in security monitoring and surveillance for buildings, airports, subways, or other critical infrastructure such as power and nuclear power plants. Sensors may also be used to improve the safety of roads by providing warnings of approaching cars at intersections. They can safeguard perimeters of critical facilities or authenticate users. Traffic Pulse Technology is an example of such applications developed by Traffic.com [52, 73]. This system is installed along major highways. The digital sensor network gathers lane-by-lane data on travel speeds, lane occupancy, vehicle counts and roadway conditions.

Military

Real-time battlefield intelligence is an essential capability of modern command, control, communications, and intelligence systems. Wireless sensors can be rapidly deployed, either by themselves (without an established infrastructure), or working with other assets such as radar arrays and long-haul communication links. They are well-suited to collect information about enemy target presence, track their movement in a battlefield and prevent enemy intrusion by monitoring borders. For instance, Boeing Co. had obtained a contract from the Department of Homeland Security of USA to implement SBInet (the Secure Borders Initiative) along the

northern and southern USA borders. One part of SBInet is the development of a technological infrastructure that facilitates the use of a variety of sensors and detection devices that enable these data to be forwarded to remote operation centers wirelessly [65].

Building monitoring and controlling

Sensors embedded in a building can drastically cut down the energy costs by monitoring the temperature, humidity and lighting conditions in the building and regulating the heating and cooling systems, ventilators, lights, and computer servers accordingly. Sensors in a ventilation system may also be able to detect biological or chemical pollutants. The high cost of wiring gives wireless sensors a big advantage over wired sensors. Coupled with the security systems of a building, the sensors may detect unauthorized intrusions or unusual patterns of activity in the building. Wireless sensors can also be used to track equipment. A wireless sensor network used for building energy monitoring and controlling can improve living conditions for the building's occupants, resulting in improved thermal comfort, improved air quality, health, safety, and productivity. At the same time, it can reduce the energy budget needed to condition the space [6]. In addition, it enables the extension and upgrading of building infrastructure with minimal effort.

Despite the importance of wireless sensor networks in building monitoring and controlling [47], there has not been much work in this area. We summarize the

projects undertaken in this area at the time of writing below:

- Chicago Fire Department (CFD) and the Berkeley Wireless Research Center (BWRC) in the Department of Mechanical Engineering at UC Berkeley worked on a project called FIRE. Firefighting can be an extremely demanding and chaotic environment in which one must make quick decisions based on little information and pay attention to many immediate events that make it difficult to efficiently and accurately complete critical tasks such as building search and rescue. The FIRE project is addressing these challenges by applying and designing new technologies such as wireless sensor networks (WSNs) and small head-mounted displays (HMDs) for firefighting, and conducting experiments and exploratory research with firefighters [87, 86]. Despite the great work and success on developing the firefighter informer and tracker in this project, no work has been done toward monitoring the building by wireless sensor network.

- The Center for the Built Environment (CBE), the Berkeley Sensor and Actuator Center (BSAC), the Berkeley Wireless Research Center (BWRC), and the Integrated Manufacturing Lab (IML), in the Department of Mechanical Engineering of UC Berkley worked on the two following projects. The first project is about airflow measurement technology and the use of sensor networks for controlling indoor temperature. This project works on multi-sensor single-actuator control of temperature by which one can use information from

a wireless sensor network to control multiple spaces in a building. As a result, energy consumption is reduced and also comfort is improved at the same time. The second project is about studying the energy implications of using sensor networks to control systems that are designed to intentionally produce indoors gradient temperature (the rate at which temperature increases or decreases relative to change in a given variable, especially distance). These systems are called underfloor air distribution (UFAD) systems. UFAD systems are commonly controlled with a single temperature sensor. Traditionally such functions have been localized in a single point. They indicate that they could significantly improve energy performance by using a sensor network with two or more sensors in each space to control such a system [21].

In the two above mentioned projects, the considered wireless sensor network is a point-to-point or multipoint-to-point (starbased) system generally with single-hop radio connectivity, utilizing static routing over the wireless network. Typically, there will be only one route from the wireless networks to the companion terrestrial/wireline forwarding node. The main disadvantages of such networks include the following: the sensor nodes do not support communications on behalf of any other sensor nodes, the forwarding node supports only static routing to the terrestrial network and/or only one physical link to the terrestrial network is present, the forwarding node does not support

data processing or reduction on behalf of the sensor nodes. As a result, these are relatively simple wireless systems, which are not as expandable, scalable and capable as meshed wireless sensor networks.

- Siemens, which has been working in building monitoring for a long time, is developing an efficient and long lasting wireless sensor network that can only monitor the temperature of the room [77]. This system would have just one capability, monitoring temperature, and it is not feasible to expand it for extra features such as in mote processing, humidity monitoring, and light status (room occupancy) due to fact that Siemens is developing its own hardware platform for forming wireless sensor networks and so far the platform that they have developed has only the capabilities of sensing temperature and doing the processing of forwarding messages to the sink.

As mentioned, there are different areas in which the use of wireless sensor network is growing fast. Areas such as building monitoring and controlling, health care and industrial applications are still in their beginning phases. Since industrial, health care and building *controlling* systems are involved with critical situations, specific standards and expectations for developing such systems should be met.

In this thesis, we decided to develop a wireless sensor network application which can address most of the limitations in previous works, for example the expandability and scalability of such systems.

The following section is about the classification of wireless sensor network applications and design problems of building monitoring system.

2.1.2 Classification of sensor network applications

For developing wireless sensor network applications, there is a need to develop application-specific protocol solutions. However, the problem in pursuing an application-specific approach is to end up developing a different protocol for each application. A careful examination of the involved trade-offs is necessary to avoid being too generic or too specific in developing the protocols. Towards this end, one classification of wireless sensor network applications can be based on [44]:

- The application level objectives
- The data delivery requirements
- The traffic characteristics

Considering the above mentioned objectives, we can design protocols that are appropriate for each class. In order to extract the best possible performance out of a large number of limited sensor devices, there is a strong need to develop class-specific solutions. Such a classification may result in partial overlaps between the application classes. However, such a classification enables us to divide and organize the design space, and allows for a systematic approach to address problems.

Wireless sensor network applications can be classified by their objectives, traffic characteristics and data delivery requirements into the following four classes: event detection and reporting, data gathering and periodic reporting, sink-initiated querying, and tracking-based applications.

Event detection and reporting

In this class of applications, motes in wireless sensor network are mostly inactive and become active when an event is detected. In addition, motes send data infrequently to the sink and when an event is detected, the motes report data to the sink along with some information about the location and nature of the event. Two important problems in such applications are first, minimizing the probability of false alarms and second, routing the event report to the sink after event detection. Examples of applications in this class are intruder detection as a part of military surveillance, detecting anomalous behavior or failures in a manufacturing process, and detection of forest fires.

Data gathering and periodic reporting

In this class, each sensor constantly produces some amount of data to be sent to the sink. The sink may recreate the spatial profile of the readings by extra information that is reported with data such as location information. Individual measurements are mostly the data that the sink is interested in. However, in some cases, the sink may require distributed computation of some function of the sensor readings. This

class also can use the first mentioned class for detecting specific events and reporting them to the sink with more priority or more redundancy for more probability of successful delivery. Applications such as monitoring the environmental conditions affecting crops or livestock, monitoring temperature, humidity and lighting in room/office buildings are examples of this category.

Sink-initiated querying

In this class, sink can query the network in general or individual sensor nodes to extract information at different abstraction levels. For the underlying communication protocols, we need (for example) effective means to address and route data to and from dynamic sets of sensors. For instance, consider an application monitoring a manufacturing process. In case of any anomalous behavior, the sensors could report such an event to the sink. Then the sink can query some specific set of sensors to obtain more information, possibly to confirm the event.

Tracking-based applications

This class usually combines some characteristics of the above three classes for tracking. For instance, when the target is detected, the sink needs to be notified promptly. Then, the sink may initiate queries to receive time-stamped location estimates of the target, so that it can calculate the trajectory and keep querying the appropriate sets of sensors. In order to design communication protocols, questions such as whether it is better to query, compute and route on the fly, or

what level of organization or connectivity should be maintained to streamline the process of tracking have to be answered. Examples of applications in this class are military or border surveillance, where one is interested in tracking an intruder or the movements of a suspicious object and also in environmental applications including tracking the movements and patterns of insects, birds or small animals.

2.1.3 Design problems for building monitoring applications

Most of the wireless sensor network applications can be categorized into one of the above mentioned classes. Even though there are common design problems for all the above mentioned classes, each of them has its own class-specific design problems as well. In this section, we explain the design problems of building monitoring applications. Each of these problems are either common design problem of all wireless sensor network applications or class-specific design problem of data gathering and periodic reporting applications (the class that includes building monitoring application):

Communication versus computation: Communicating information over the wireless channel consumes more energy than computing [4]. In several sensor network applications, it is possible to perform local processing within the network to compress or aggregate the gathered data. It is also possible to compute analyzed information from gathered data within the sensor node rather than doing that by forwarding all gathered data to the sink and analyzing them at the end user

application. Any form of in-network data aggregation or in-mote data processing may reduce the amount of data that is actually sent to the sink, and this results in considerable energy savings.

Routing: One of the main design goals of wireless sensor networks is to carry out data communication while trying to prolong the lifetime of the network and prevent connectivity degradation by employing aggressive energy management techniques [50, 51]. The design of routing protocols is influenced by many challenges. These challenges must be overcome before efficient communication can be achieved in a wireless sensor network. These challenges can be attributed to multiple factors including energy constraints, limited computing and communication capabilities, the dynamically changing environment within which sensors are deployed, unique data traffic models, and application-level quality of service requirements [67]. The two first challenges are common to all wireless sensor networks applications. However, the two latter challenges are class-specific design problems of such applications. In Section 2.3, we explain different categories of routing algorithms and go into the details of those that are in the interest of wireless sensor networks for building monitoring.

Idle-listening and power-saving algorithms: A considerable amount of energy is consumed by the radio in idle-listening. This can have a significant impact on the network lifetime [76]. It would be reasonable to turn off the radio module

of nodes, and only keep the sensing module on. However, most sensor networks require the use of multi-hop communication, since the communication range of an individual sensor can be much smaller than the size of the region. Hence, it is important for the sensor nodes to remain awake for some time, in order to be ready to relay the data to and receive the data from the other sensor nodes. One way to curb the energy-expenditure due to idle listening is using a power saving mode [41, 93]. In such schemes, nodes turn off their radios periodically either independently [41] or in a co-ordinated fashion (synchronization) [93]. This enables the node to save its battery energy for the duration in which its radio is turned off. However, synchronization has communication overheads associated with it, and these trade-off issues have been addressed in several papers such as [22, 25].

Connectivity and coverage: In many sensor network applications, the user does not have complete control over the placement of each node. Consequently, once the nodes have been deployed, some of them could end up in locations that are wireless-unfriendly due to shadowing. Even for applications where the user has control over node deployment, the nodes could experience bad fades due to changes in the surrounding environment, or the radio frequency interference. Sometimes, nodes could experience temporary or permanent hardware failure due to changing environmental conditions such as heat and humidity, and this may impact the network connectivity and coverage. Results on network connectivity and coverage in large sensor networks with random node deployment and/or under possible node

failures are shown in [26, 75] .

2.2 Wireless sensor network platforms

A wireless sensor network consists of sensor nodes (motes) each of which, in addition to one or more sensors, has a radio transceiver or other wireless communication devices with a small processing unit and an energy source (usually a battery). The envisaged size of a single sensor node can vary from shoe-box-sized nodes down to devices with the size of a grain of dust [67]. The cost of each mote is similarly variable, ranging from hundreds of dollars to tens of dollars, depending on the size of the sensor network and the complexity required by individual motes [67]. However, cost of each mote is expected to be a few cents in the near future [37]. Size and cost constraints on sensor nodes result in corresponding constraints on resources such as energy, memory, computational speed and bandwidth [67]. In this section, we discuss the technology of a mote's hardware, mainly talking about how a wireless sensor network is operated and what kinds of applications and algorithms can be implemented on such networks.

2.2.1 Processing unit

Sensor nodes need processing units in order to communicate to other nodes, process and gather sensor data. The central processing unit of a sensor node determines

a large degree of both the energy consumption as well as the computational capabilities of a sensor node.

Microcontroller as the most common processing unit in sensor node can perform the tasks, process data and control the functionality of other components. Other alternatives that can be used as a controller are general purpose desktop microprocessor, digital signal processors, field programmable gate array and application-specific integrated circuit.

Microcontroller is the most suitable choice for sensor nodes because of their flexibility to connect to other devices, ability to be programmed, and low power consumption, which is due to the capability of these devices which can go to sleep state and keep some parts active. Nowadays, microcontroller includes not only memory and processor, but also non-volatile memory and interfaces such as ADCs, UART, SPI, counters and timers. This way, it can collaborate with sensors and communication devices such as short range radio [84].

Microprocessor is not a good choice for sensor nodes, since energy consumption of microprocessor is more than that of microcontroller. Digital Signal Processor (DSP) is appropriate for broadband wireless communication. However, in wireless sensor networks, the wireless communication should be modest. It means that it should be simpler and easier to process the modulation and signal processing tasks. Therefore the advantages of DSP are not useful in wireless sensor nodes. Field Programmable Gate Arrays (FPGA) can be reprogrammed and reconfigured

according to requirements, but the time and energy that it takes is more than microcontrollers and it is not also possible to turn off separate blocks of it [35]. Therefore FPGA is not advisable. Application Specific Integrated Circuits (ASIC) are specialized processors designed for a specific given application. ASIC provides the functionality in the form of hardware. However, microcontrollers provide it through software.

2.2.2 Radio transceiver

Three possibilities for wireless transmission media are radio frequency, optical communication (laser) and Infrared. Laser requires less energy than the two others, but needs line of sight for communication. It is also sensitive to the atmospheric conditions. Infrared like laser needs no antenna but is limited in its broadcasting capacity. Radio frequency is the most appropriate media that fits into the most of wireless sensor network applications.

While most ongoing work in IEEE 802 wireless working groups is focused on increasing the data rates, throughput, and QoS, the IEEE 802.15.4 task group is aiming for other goals [27]. The focus of IEEE802.15.4 is on very low power consumption, very low cost, low data rate to connect devices that previously have not been networked, and to allow applications that cannot use current wireless specifications. Two physical layer specifications were chosen to cover the 2.4 GHz worldwide band and the combination of the 868 MHz band in Europe, the 902

MHz band in Australia, and the 915 MHz band in the United States. Both physical layers are direct sequence spread spectrum (DSSS) solutions. One of the IEEE 802.15.4 physical layers operates in the 2.4 GHz industrial, scientific and medical band with nearly worldwide availability [33]. This band is also used by other IEEE 802 wireless standards. Wireless standards such as 802.11 (WiFi), 802.15.1 (Bluetooth), 802.15.4 (ZigBee) are being considered as some of the physical interfaces [58].

Wireless sensor network uses the communication frequencies between about 433 MHz and 2.4 GHz. The functionality of both transmitter and receiver are combined into a single device known as a transceiver. The current generation of radios has a built-in state machine that performs transceiver's operational modes automatically. Radios used in transceivers operate in four different modes: transmit, receive, idle, and sleep. Radios operating in idle mode result in power consumption, almost equal to power consumed in receive mode [89]. Thus, it is better to completely shut down the radios rather than in the idle mode when it is not transmitting or receiving. Also, significant amount of power is consumed when switching from sleep mode to transmit mode.

2.2.3 Sensor

Sensor is a transducer that converts a physical phenomenon such as heat and light into electrical or other types of signals that may further be manipulated.

Typical sensors that can be used with motes are those with ability to measure the temperature, light, humidity, position, acceleration, velocity, vibration, pressure, weight, stress, chemical concentration etc. Depending on the sensor capability, size, accuracy and technology, price of each mote with such sensors can vary from few dollars to hundreds of dollars. For example, motes with positioning systems like GPS are much more expensive than a mote with just temperature, light and humidity sensors. Different Sensors can have different impact on wireless sensor network applications such as decreasing lifetime of each mote in the network by consuming lots of energy or by sensing physical environment with low accuracy. Selection of sensors should be done with consideration of the phenomenon that is supposed to be sensed and the application that needs to be run over motes.

2.2.4 Selection criteria

Most important selection criteria for an embedded computer processor (mote) for the building monitoring applications are:

- Processing power
- Communication capabilities
- Sensors
- Power consumption
- Memory

- PCI interface
- Availability
- Cost

For sensor node selection, there are other factors that should be considered beside CPU, radio transceiver and sensors. Lifetime of each mote depends on power consumption of different mote's mode such as processing data, transmitting data or listening over the radio. Microcontroller and flash memory of motes are considerable, since they can define the processing functionality of the mote and data storing capabilities with in mote data processing of sensed phenomenon. Moreover, Peripheral Communication Interface (PCI) is important to be considered for programming, debugging and communication purposes.

Due to the diversity of applications, it is unlikely that a single node platform would be able to span the energy, cost, functionality, form factor and other requirements of all the applications. However, the motes developed by UC Berkeley are notable examples of sensor nodes, used by a variety of academic and industrial organizations. These motes provide very small form factors, long lifetimes, reasonable processing and memory capabilities.

The Tmote Sky is the most recently developed commercially available version, constructed from commercial-of-the-shelf (COTS) components to provide the greatest possible flexibility. Table 1 gives an overview of the mote evolution headed by the Tmote sky. Note that the Telos mote shown in Table 1 is more precisely

the Telos mote Revision A and Tmote sky includes more sophisticated hardware, a new microcontroller, and a variety of additional feature [36].

Table 1: The evolution of the UCB mote platforms [62]

Mote type	Wec & Rene	Rene 2 & Dot	Mica	Mica 2	Telos	Tmote sky
Year	1998	2000	2001	2002	2004	2005
Microcontroller						
Type	AT90LS8535	ATmega163	ATmega128		MSP430 F149	MSP430 F1611
Programming memory(KB)	8	16	128		60	48
RAM(KB)	0.5	1	4		2	10
Active power(mW)	15	15	15	60	3	3
Sleep power(μW)	45	45	75	75	6	6
Wakeup Time(μS)	1000	36	180	180	6	6
Nonvolatile storage						
Chip	24LC256		AT45DB041B		ST M24M01S	ST M25P80
Connection type	I2C		SPI		I2C	SPI
Size(KB)	32		512		128	1024
Communication						
Radio	TR1000		TR1000	CC1000	CC2420	CC2420
Data rate(kbps)	10		40	38.4	250	250
Modulation type	OOK		ASK	FSK	O-QPSK	O-QPSK
Receive power(mW)	9		12	29	38	38
Transmit power at 0dBm(mW)	36		36	42	35	35
Power consumption						
Minimum operation(V)	2.7	2.7	2.7		1.8	2.0
Total active power(mW)	24		27	89	41	41
Programming & sensor interface						
Expansion	none	51-pin	51-pin		10-pin	10-pin & 6-pin IDC
Communication	IEEE 1284 and RS232(requires additional hardware)				USB	
Integrated sensors	no		no		yes	yes

The Tmote sky is a low power and high data rate platform. It includes the largest on-chip RAM size (10kB) of any mote. It utilizes IEEE 802.15.4 radio (250kbps, 2.4 MHz band) and an integrated antenna/SMA connector, which provides a communication range up to 125 meters. Tmote sky offers a number of integrated peripherals including a 12-bit ADC and DAC, Timer, I2C, SPI (Serial Peripheral Interface), UART (Universal Asynchronous Receiver and Transmitter) bus protocols and a DMA (Direct Memory Access) controller. It provides a USB interface for programming, debugging and data collection. Furthermore, it supports a hardware protected external flash (1Mb), fast wake up from sleep ($<6\mu$s).

This mote can accomplish sensing due to on-board humidity, light and temperature sensors, thus increasing the robustness while decreasing cost and size. The low power operation of the Tmote sky is due to the ultra low power Texas Instruments MSP430 microcontroller (16-bit RISC processor). Furthermore, it uses an I2C digital switch to prevent unwanted conventional serial port signals from reaching the microcontroller. In order to obtain direct access between the Tmote sky and USB controller, the I2C protocol should be implemented and sent over the RTS and DTR lines. Finally, the Tmote sky may be powered by two AA batteries for couple of months and needs no batteries at all if always attached to the USB port. More detailed information is provided in MoteIV website [36].

2.3 Wireless sensor network routing algorithms

A routing algorithm is one of the most important component of a wireless sensor network. As we know, a wireless sensor network is not similar to wired back bone network which can use end to end addressing for routing the data in the network and it is also different from ad hoc networks in which each node has competitively much higher computational resources. Therefore, meeting the design requirements of routing algorithms for wireless sensor network presents a distinctive and unique set of challenges. These challenges can be attributed to multiple factors including energy constraints, limited computing and communication capabilities, the dynamically changing environment within which sensors are deployed, unique

data traffic models, and application-level quality of service requirements [67].

Routing protocols can be classified according to the network structure as flat, hierarchical, or location-based [3, 5]. In flat-based routing, all nodes are typically assigned equal roles or functionalities. In hierarchical-based routing, nodes will play different roles in the network. For example, hierarchical protocols aim at clustering the nodes so that cluster heads can do some aggregation and reduction of data in order to save energy. Location-based routing exploits information about the location of the sensors in order to forward data among the network in an energy-efficient way. In the following, we explain the different categories of routing algorithms and explain in detail some specific routing algorithms that are relevant to developing building monitoring application using a wireless sensor network.

2.3.1 Flat routing

In flat networks, sensor nodes typically play the same role and collaborate together to perform the sensing task. The lack of a global identification due to the large number of nodes present in the network and their random placement, typical of many specific wireless sensor network applications, makes it hard to select a specific set of sensors to be queried. This can often cause redundant transmission of data from each sensor node with consequent inefficient energy consumption. A useful solution is the definition of routing protocols that are able to select appropriate sets of forwarding sensor nodes and to utilize data aggregation during the relaying of

data. This routing policy is known as data-centric routing, which is different from traditional address-based routing where routes are created between addressable nodes. In data-centric routing, the sink sends queries to certain regions and waits for data from the sensors located in the selected regions. Attribute-based naming is necessary to specify the properties of data requested in the queries. Early work on data-centric routing (e.g., SPIN and directed diffusion [92]) were shown to save energy through data negotiation and elimination of redundant data. These two protocols motivated the design of many other protocols that follow a similar concept. The following is the explanation of SPIN, directed diffusion and other related flat routing algorithms in the scope of this thesis:

Flooding and gossiping: Flooding and gossiping [1] [30] are two classical data-relay mechanisms that do not require any topology maintenance. In flooding, each sensor receiving a data packet broadcasts it to all of its neighbors, regardless of whether or not a neighbor has already received the data from another node. This process continues until the packet arrives at the destination. Gossiping is a slightly enhanced version of flooding. When a node receives a packet, it randomly chooses one of its neighbors to which it forwards the packet. Flooding is very easy to implement, but it has several drawbacks: implosion caused by duplicated messages sent to same node, overlap when sensor nodes cover overlapping geographic areas and therefore they collect overlapping pieces of data, resource blindness since in

[1]The terms flooding and gossiping are used here as defined in [30]

classic flooding nodes do not modify their activities based on the amount of energy available to them at a given time. Gossiping does not solve the problem of overlap, even though it can avoid implosion by just selecting a random next node rather than broadcasting. However, this causes delays in propagation of data.

Sensor Protocols for Information via Negotiation (SPIN): SPIN [40] is among the early works to pursue a data-centric routing mechanism. The idea behind SPIN is to name the data using high level descriptors or meta-data. Before transmission, meta-data are exchanged among sensors via a data advertisement mechanism, which is the key feature of SPIN. Each node, upon receiving new data, advertises them to its neighbors and interested neighbors. It means that those who do not have the data, retrieve the data by sending a request message. SPIN meta-data negotiation solves the classic problems of flooding such as redundant information passing, overlapping of sensing areas and resource blindness. Thus, it achieves a lot of energy efficiency. There is no standard meta-data format and it is assumed to be application specific, e.g., using an application level framing. There are three messages defined in SPIN to exchange data between nodes. These are ADV message to allow a sensor to advertise particular meta-data, REQ message to request the specific data and DATA message that carries the actual data. One of the advantages of SPIN is that topological changes are localized, since each node needs to know only its single-hop neighbors. SPIN almost halves the redundant data in comparison to flooding. However, the SPIN data advertisement mechanism

cannot guarantee the delivery of the data. For instance, if the nodes that are interested in the data are far away from the source node and the nodes between source and destination are not interested in those data, such data will not be delivered to the destination at all.

Directed diffusion: In [24], C. Intanagonwiwat et al. have proposed a popular data aggregation paradigm for wireless sensor networks, called directed diffusion. Directed diffusion is a data-centric and application-aware paradigm in the sense that all data generated by sensor nodes is named by attribute-value pairs. The main idea of the data-centric paradigm is to combine the data coming from different sources (in-network aggregation) by eliminating redundancy, minimizing the number of transmissions, resulting in saving network energy and prolonging its lifetime. Unlike traditional end-to-end routing, data-centric routing routes from multiple sources to a single destination, which allows in-network consolidation of redundant data. In directed diffusion, sensors measure events and create gradients of information in their respective neighborhoods. The base station requests data by broadcasting its interests to the motes holding the data. An interest describes a task required to be done by the network. An interest diffuses through the network hop-by-hop, and is broadcast by each node to its neighbors. As the interest is propagated throughout the network, gradients are set up to draw data satisfying the query towards the requesting node, meaning that a base station may query for data by disseminating interests and intermediate nodes propagate these interests.

Each sensor that receives the interest sets up a gradient toward the sensor nodes from which it receives the interest. This process continues until gradients are set up from the sources back to the base station. In order to reduce communication costs, data is aggregated on the way. The goal is to find a good aggregation tree that gets the data from source nodes to the sink.

Directed diffusion differs from SPIN in terms of the on demand data querying mechanism it has. In directed diffusion, the sink asks the sensor nodes if specific data are available by flooding some interest messages. In SPIN, sensors advertise the availability of data, while allowing interested nodes to query that data. Directed diffusion has many advantages. Since it is data-centric, all communications are neighbor-to-neighbor with no need for a node addressing mechanism. In addition to sensing, each node can do aggregation and caching. Caching is a big advantage in terms of energy efficiency and delay. In addition, directed diffusion is highly energy-efficient, since it is on demand and there is no need for maintaining a global network topology. However, directed diffusion cannot be applied to all sensor network applications, since it is based on a query-driven data delivery model. In addition, the naming schemes used in directed diffusion are application dependent and each time should be defined a priori. Moreover, the matching process for data and queries might require some extra overhead at the sensors.

Minimum Cost Forwarding Algorithm (MCFA): The MCFA [92] exploits the fact that the direction of routing is always known, that is, towards the fixed

external base-station. Hence, a sensor node does not need to either have a unique id or maintain a routing table. Instead, each node maintains the least cost estimation from itself to the base station. Each message to be forwarded by the sensor node is broadcast to its neighbors. When a node receives the message, it checks whether it is on the least cost path between the source sensor node and the base station. If this is the case, it rebroadcasts the message to its neighbors. This process repeats until the base station is reached. In MCFA, each node should know the least cost path estimation from itself to the base station. This is obtained as follows: the base station broadcasts a message with the cost set to zero while every node initially set its least cost to the base station to infinity. Each node, upon receiving the broadcast message originated at the base station, checks to see if the estimation in the message plus the link on which it is received is less than the current estimation. If so, the current estimation and the estimation in the broadcast message are updated. If the received broadcast message is updated, then it is resent. Otherwise, it is purged and nothing further is done. However, the previous procedure may result in some nodes having multiple updates and those nodes far away from the base station will get more updates from those closer to the base-station. This routing algorithm is in the flat routing category, even though it is not data-centric like direct diffusion and SPIN. This routing algorithm is simple to implement. However, it is not energy-efficient and makes lots of redundant data.

Mintroute: Mintroute [88] is a collection routing protocol (for data gathering and periodic reporting class of applications) that chooses a parent based on the expected number of transmissions (ETX) to the root of a collection tree. Commonly, the ETX estimation is the sum of the link qualities, where zero represents a perfect link. A parent's quality is its advertised value, sent periodically via route update beacons, plus the quality of the link between parent and child (lower values are better). Link connectivity statistics are captured dynamically through an efficient yet adaptive link estimator. Routing decisions exploit such connectivity statistics to achieve reliability. Link status and routing information are maintained in a neighborhood table with constant space regardless of cell density. Mintroute uses per-hop retransmissions to make additive quality an accurate measure. It has two kinds of traffic: route update beacons it broadcasts, and data messages it unicasts to the currently selected parent.

Link estimation has been a major component of early Mintroute implementations. As it was specific to Mintroute, this information could not be easily shared. Integration of the link estimator into Mintroute caused the TinyOS distribution to go for numerous Mintroute implementations, each with a different integrated link estimator. This routing algorithm is not data-centric and not even address-centric. It tries to find the best route to the base station in the fastest way. Even though, it does not consider energy in its routing in order to provide quality of service for real time data reporting, it tries to be fault tolerant by sending duplicate message.

In addition, it is simple and scalable.

MultihopLQI: MultihopLQI [54] is a collection routing protocol that provides a best-effort, multi-hop delivery of packets to the root of a tree. The general approach used is to build one or more collection trees, each of which is rooted at a base station. When a node has data that needs to be collected, it sends the data up the tree, and it forwards collection data that other nodes send to it. Sometimes, depending on the form of data collection, systems need to be able to inspect packets as they go by, either to gather statistics, compute aggregates, or suppress redundant transmissions. When a network has multiple base stations that act as root nodes, rather than one tree, it has a forest of trees. By picking a parent node, a collection protocol implicitly joins one of these trees. Collection provides a best-effort, multi-hop delivery of packets to one of a network's tree roots: it is an anycast protocol. The semantics is that the protocol will make a reasonable effort to deliver the message to at least one of the roots in the network. There are however no guarantees of delivery, and there can be duplicates delivered to one or more roots. There are also no ordering guarantees. It uses a link quality estimation by using special piece of physical layer data the radio provides (the Link Quality Indicator (LQI) value). This piece of data is provided by CC2420 radio module [83]. In this way, MultiHopLQI reduces the control traffic. MultihopLQI has less energy cost and less overhead than Mintroute [82].

Arbor: Arbor [8] is a collection routing protocol similar to MultihopLQI and Mintroute. Arbor is a tree-based collection protocol. Some number of nodes in a network advertise themselves as tree roots. Nodes form a set of routing trees to these roots. Arbor is address-free in that a node does not send a packet to a particular root instead, it implicitly chooses a root by choosing a next hop. Nodes generate routes to roots using a routing gradient. This routing algorithm is designed for relatively low traffic rates. It finds the best route to the sink based on the expected number of transmissions (ETX). Arbor uses dynamic ETX in which combined beacon and data packets lost ratio are used instead of just beacon packets lost ratio. Arbor has higher traffic control and cost than Mintroute and MultihopLQI.

Other flat-based routing algorithms: There are other algorithms that follow the concept of data-centric approach for data aggregation used first in directed diffusion [24]. Rumor routing [12] is a variation of directed diffusion and is mainly intended for applications where geographic routing is not feasible. Constrained Anisotropic Diffusion Routing (CADR) [15] is a protocol that strives to be a general form of directed diffusion. The idea is to query sensors and route data in a network in order to maximize the information gain, while minimizing the latency and bandwidth. Energy Aware Routing [74], a destination initiated reactive protocol with the objective of increasing network lifetime, is similar to directed diffusion.

However, it differs in the sense that it maintains a set of paths instead of maintaining or enforcing one optimal path at higher rates. Schurgers et al. [70] have proposed a slightly changed version of directed diffusion, called Gradient-Based Routing (GBR). The idea is to keep the number of hops when the interest is diffused through the network. Hence, each node can discover the minimum number of hops to the sink, which is called height of the node. COUGAR, a data-centric protocol that views the network as a huge distributed database system is proposed by Yao and Gehrke [91]. The main idea is to use declarative queries in order to abstract query processing from the network layer functions such as selection of relevant sensors and utilize in-network data aggregation to save energy. A fairly new data-centric mechanism for querying sensor networks is ACtive QUery forwarding In sensoR nEtworks (ACQUIRE) [68]. The approach views the sensor network as a distributed database and is well-suited for complex queries that consist of several sub-queries.

2.3.2 Hierarchical routing

Hierarchical or cluster-based routing, originally proposed in wireline networks, is a well-known technique with special advantages related to scalability and communication efficiency. As such, the concept of hierarchical routing is also utilized to perform energy efficient routing in wireless sensor networks. In wireless sensor network with hierarchical architecture, higher energy nodes can be used to process

and send the information, while low-energy nodes can collaborate with each other in monitoring the interested area and gathering data. This means the creation of clusters with assigning of special tasks to cluster heads (such as data fusion and data forwarding) achieves system scalability, increased network lifetime, and energy efficiency. Hierarchical routing is mainly two-layer routing, where one layer is used to select cluster heads and the other layer is used for routing. Cluster formation is typically based on the energy conservation of sensors and sensors' proximity to the cluster head [45].

Low-Energy Adaptive Clustering Hierarchy (LEACH) [31] is one of the most popular hierarchical routing algorithms for sensor networks. The idea is to form clusters of the sensor nodes based on the received signal strength and use local cluster heads as routers to the sink. LEACH is completely distributed and requires no global knowledge of network. Although LEACH is able to increase the network lifetime, there are still a number of issues about the assumptions used in this protocol. LEACH assumes that all nodes can transmit with enough power to reach the base station in one hop if needed. It also supposes that each node has computational power to support different MAC protocols. It also assumes that nodes always have data to send, and nodes located close to each other have correlated data. Therefore, it is not applicable to networks deployed in large regions. Furthermore, the idea of dynamic clustering brings extra overhead such as head changes and advertisements, which may diminish the gain in energy consumption.

The idea proposed in LEACH has been an inspiration for many hierarchical routing protocols such as Power-Efficient Gathering in Sensor Information Systems (PEGASIS) [46] and Threshold-sensitive Energy Efficient Network protocols (TEEN and APTEEN) [48, 49]

2.3.3 Location based routing

This kind of routing protocol exploits information about the location of the sensors in order to forward data among the network modes in an energy-efficient way. The location of nodes may be available directly from a GPS system or by implementing some localization protocols specifically studied for wireless sensor networks. Many solutions for nodes localization have been proposed in the literature. Some of the protocols are designed primarily for mobile Ad Hoc networks and consider the mobility of nodes during the design [43, 66, 90]. However, they are also well-applicable to sensor networks where there is less or no mobility.

2.3.4 Selection criteria

Wireless sensor networks have several restrictions such as limited energy supply, limited computing power, and limited bandwidth of the wireless links connecting sensor nodes. One of the main design goals of wireless sensor networks is to carry out data communication while trying to prolong the lifetime of the network and prevent connectivity degradation by employing aggressive energy management

techniques. The design of routing protocols is influenced by many challenging factors. These factors must be overcome before efficient communication can be achieved. In the following, we summarize some of the routing challenges for wireless sensor network applications to monitor buildings and different categories of routing algorithms to address each challenge.

- **Data reporting model:** Data reporting can be categorized as either time-driven (continuous), event-driven, query-driven, and hybrid [91]. The time-driven delivery model is suitable for applications that require periodic data monitoring. As such, sensor nodes periodically switch on their sensors and transmitters, sense the environment and transmit the data of interest at constant periodic time intervals. In event-driven and query-driven models, sensor nodes react immediately to sudden and drastic changes in the value of a sensed attribute or a query is generated by the base station. A combination of two previous models is also possible. Our application, which is classified under data gathering and reporting class, is using time-driven (continuous) data reporting model. The routing protocol for such an application is highly influenced with regard to energy consumption and route stability. Because of periodic data reporting by such applications, query based routing algorithms are not suitable for them. In time-driven data reporting applications, due to the significant amount of data that is continuously transmitted to the sink, data can be aggregated on the way to the sink, thus reducing traffic and

saving energy. For this purpose, algorithms such as directed diffusion are appropriate as well.

- **Node/link heterogeneity:** Mostly sensor nodes are assumed to be homogeneous, meaning that they have equal capacity in terms of computation, communication, and power. However, depending on the application, a sensor node can have different role or capability. The existence of a heterogeneous set of sensors raises many technical issues related to data routing. For example, some applications might require a diverse mixture of sensors for detecting motion via acoustic signatures, and capturing the image or video that represents tracking of moving objects. These special sensors can be either deployed independently or the different functionalities can be included in the same sensor nodes. Even data reading and reporting can be generated from these sensors at different rates subject to diverse quality of service constraints, and can follow multiple data reporting models. For example, hierarchical protocols designate a cluster-head node different from the normal sensors. These cluster-heads can be chosen from the deployed sensors or can be more powerful than other sensor nodes in terms of energy, bandwidth, and memory. Hence, the burden of transmission to the base station is handled by the set of cluster-heads. In our application, motes are homogeneous. This makes the system easy to develop, implement, maintain and deploy in a building. Thus, hierarchical routing is not suitable for our application.

- **Node deployment and fault tolerance:** Node deployment in wireless sensor networks is application-dependent and affects the performance of the routing protocol. The deployment can be either randomized or deterministic. In random node deployment, the sensor nodes are scattered randomly creating an infrastructure in an Ad Hoc manner. However, in deterministic deployment, the sensors are manually placed and data is routed through predetermined paths. In deterministic deployment, some sensor nodes may fail or be blocked due to lack of power, physical damage, or environmental interference. The failure of sensor nodes should not affect the overall task of the sensor network. If many nodes fail, MAC and routing protocols must accommodate formation of new links and routes to the data collection base stations. This may require actively adjusting transmit powers and signaling rates on the existing links to reduce energy consumption, or rerouting packets through neighbor nodes where more energy is available. In our application, node deployment is deterministic in the way that there is one sensor node per room/office of the building. However, our application needs to be fault tolerant. In the other words, we do not want some part of network to be disconnected from the others due to the failure of a small set of motes. Although the node deployment in our application is deterministic, we need a routing algorithm where a mote periodically checks its one-hop neighbors based on their link quality, and connectivity for selecting the best forwarding

neighbor.

- **Data aggregation:** Since sensor nodes might generate significant redundant data, similar packets from multiple nodes can be aggregated so that the number of transmissions would be reduced. Data aggregation is the process of combining the data from different sources by using functions such as suppression (eliminating duplicates), min, max and average [39]. Some of these functions can be performed either partially or fully in each sensor node by allowing sensor nodes to conduct in-network data reduction. Recognizing that computation would be less energy consuming than communication, substantial energy savings can be obtained through data aggregation. Such algorithms can be useful when sources send information with some intermediate and non deterministic level of redundancy. If all sources send completely different information with no redundancy, such applications would work like address-centric routing algorithms except the fact that they use more energy for processing the data to check the possibility of their aggregation. In our building monitoring system, if there is more than one sensor node in one place for data gathering and reporting, data aggregation would help in reducing redundant data and conserve energy.

- **Energy considerations:** During the creation of an infrastructure, the process of setting up the routes is greatly influenced by energy considerations. Since the transmission power of a wireless radio is proportional to distance

squared or even higher order in the presence of obstacles, multi-hop routing will consume less energy than direct communication. However, multi-hop routing introduces significant overhead for topology management and medium access control. Direct routing would perform well enough if all the nodes were very close to the sink. In our application, motes are scattered through out the building with a base station in each floor. Within buildings with large space in each floor, using multi-hop routing is unavoidable.

- **Quality of service:** In some applications, data should be delivered within a certain period of time from the moment it is sensed, otherwise the data will be useless. Therefore, bounded latency for data delivery is another condition for time-constrained applications. However, in many applications, conservation of energy, which is directly related to network lifetime, is considered relatively more important than the quality of sent data. As the energy gets depleted, the network may be required to reduce the quality of the results in order to reduce the energy dissipation in the nodes and hence lengthen the total network lifetime. This is mostly the case for wireless sensor networks in which sensor nodes are out of reach or very expensive to renew their energy source, or the quality and time of sensed data is not that much critical or important. In our application, the quality of service has more importance than the energy of the motes. We need to have real time data in our building monitoring system. The sensed data in our application also are critical toward the safety

of building tenants in cases such as sudden temperature drop or rise.

As a summary, we can conclude that flat routing is the most appropriate category among the mentioned routing categories for wireless sensor network application for building monitoring (regarding to the fact that all sensor nodes are homogeneous). In the flat routing category, a routing algorithm that can provide quality of service with fault tolerance in deterministic node deployment is appropriate for our application. In addition, we are interested in a routing algorithm that considers energy constraints of sensor nodes without sacrificing other above mentioned factors. Furthermore, in our application because of not having redundant data due to the fact that there is one mote in each room/office of the building, we do not use data aggregation. Using data aggregation in this case causes more in mote processing and delay without reducing any data. Thus, the best choices for such application would be a routing protocol similar to Mintroute, MultihopLQI or Arbor routing algorithm, which address most of the mentioned challenges.

Mintroute and Arbor use the number of transmission (ETX) for selecting best neighbor to forward the packet. Mintroute calculates the ETX based on beacon messages lost ratio calculated in link layer. Arbor uses ETX based on beacon and data messages to calculate better estimation. However, MultihopLQI is using the Link Quality Indication (LQI), a feature of the CC2420 radio that is implemented on Tmote Sky motes and gives an instant characterization of the incoming signal for a received packet, to estimate link qualities. As a result, MultihopLQI uses less

in mote processing and traffic control messages. In addition, MultihopLQI is more energy efficient in comparison to Mintroute and Arbor routing algorithms [82]. The rate of delivery and quality of service are almost the same in all three routing algorithms [8]. These routing algorithms provide multi-hop delivery of packets to the root of a tree by means of one or more collection trees. In our application, we use a multi-hop routing algorithm called *MultiHop* which uses Link Quality Indications (LQI) from radio for best neighbor selection. In our system, the motes in each floor have unique addresses with the same group id. In the other words, in each floor, group id of the motes is the same and each floor has unique group id. Since there are not many rooms in each floor of the buildings (less than 100 motes might be required), we have one sink in each floor and the motes in each floor generates routes for a single tree rooted to the sink in that floor. The rest of the routing algorithm in our application is implemented mostly based on the methods and specifications of MultihopLQI and Mintroute routing algorithms. The routing algorithm of our application is explained in detail in Subsection 3.3.5.

Chapter 3

Automated Building Monitoring System

In this chapter, we discuss the methodology of designing and developing an Automated Building Monitoring System. We proposed this system with wireless sensor network for building monitoring purposes in order to address the problem defined in Section 1.2. Our system is divided into three different subsystems: The end user application, wireless sensor network and gateway/server. Each of these should meet a set of requirements and specifications as explained in Section 1.2. First we mention what technologies have been used in the development of this system. Second, we explain the architecture of the system. Finally, we break down the parts of the system.

3.1 Technologies

3.1.1 NesC

NesC (Network embedded systems C) [56] is a component-based, event-driven programming language used to build applications for the TinyOS platform [32]. NesC is dialect of the C programming language with components wired together optimized for the memory limitations of sensor networks [23]. The basic concepts behind NesC are as follows:

- Construction and composition are separated. Programs are built out of components, which are assembled (wired) to form whole programs. Components define two scopes, one for their specification (containing the names of their interface instances) and one for their implementation. Components have internal concurrency in the form of tasks. Threads of control may pass into a component through its interfaces. These threads are rooted either in a task or a hardware interrupt.

- Specification of component behavior is in terms of a set of interfaces. Interfaces may be provided or used by the component. The provided interfaces are intended to represent the functionality that the component provides to its user, the used interfaces represent the functionality the component needs to perform its job.

- Interfaces are bidirectional. They specify a set of functions to be implemented

by the interfaces provider (commands) and a set to be implemented by the interfaces user (events). This allows a single interface to represent a complex interaction between components. Typically commands call downwards from application components to those closer to the hardware, while events call upwards.

- Components are statically linked to each other via their interfaces. This increases runtime efficiency, encourages robust design, and allows for better static analysis of programs.

- NesC is designed under the expectation that code will be generated by whole-program compilers. This should also allow for better code generation and analysis.

- The concurrency model of NesC is based on run-to-completion tasks, and interrupt handlers that may interrupt tasks and each other. The NesC compiler signals the potential data races caused by the interrupt handlers.

We used the NesC 1.1.3 programming language for developing necessary code for sensor nodes.

3.1.2 TinyOS

TinyOS is an open source component-based operating system and platform targeting wireless sensor networks [60, 32]. TinyOS is an embedded operating system

written in the NesC programming language as a set of co-operating tasks and processes. Its supplemental tools come mainly in the form of shell script front-ends. Associated libraries and tools such as the NesC compiler are mostly written in C.

TinyOS programs are built out of software components, some of which present hardware abstractions. Components are connected to each other using interfaces. TinyOS provides interfaces and components for common abstractions such as packet communication, routing, sensing, actuation and storage. TinyOS's component library includes network protocols, distributed services, sensor drivers, and data acquisition tools, all of which can be used as-is or be further refined for a custom application. TinyOS's event-driven execution model enables fine-grained power management yet allows the scheduling flexibility made necessary by the unpredictable nature of wireless communication and physical world interfaces. TinyOS has several important features. Three of them are as follows:

- Component-based architecture: TinyOS provides a set of reusable system components. An application connects components using a wiring specification that is independent of component implementations; each application customizes the set of components it uses. Although most OS components are software modules, some are thin wrappers around hardware and the distinction is invisible to the developer. Decomposing different OS services into separate components allows unused services to be excluded from the application.

- Tasks and event-based concurrency: There are two sources of concurrency in TinyOS: tasks and events. Tasks are a deferred computation mechanism. They run to completion and do not interrupt each other. Components can post tasks. The post operation immediately returns, deferring the computation until the scheduler executes the task later. Components can use tasks when timing requirements are not strict. This includes nearly all operations except low-level communication. To ensure low task execution latency, individual tasks must be short, meaning that lengthy operations should be spread across multiple tasks. The lifetime requirements of sensor networks prohibit heavy computation, keeping the system reactive. Events also run to completion, but may interrupt the execution of a task or another event.

- Non-blocking behavior: TinyOS has a single stack. Therefore, all I/O operations that last longer than a few hundred microseconds are asynchronous and have a callback. To enable the native compiler to better optimize across call boundaries, TinyOS uses NesC's features to link these callbacks, called events, statically. While being non-blocking enables TinyOS to maintain high concurrency with a single stack, it forces programmers to write complex logic by combining together many small event handlers.

TinyOS started as a collaboration between the University of California, Berkeley and Intel Research center since 2000, and has grown to a be an international

consortium, the TinyOS Alliance. We have used TinyOS Version 1.2 in this research.

3.1.3 Cygwin

Cygwin is a collection of tools originally developed by Cygnus Solutions to provide a command line and programming interface familiar to Unix users in Microsoft Windows [79]. While Cygwin provides programming language header files and libraries making it possible to recompile or port Unix applications for use on computers running Microsoft Windows operating systems, it does not provide binary executable programs capable of running without Cygwin installed. It consists of two parts: first, a DLL (Cygwin.dll), which acts as a Linux API emulation layer providing substantial Linux API functionality and second, a collection of tools which provide Linux look and feel. The Cygwin DLL works with all x86 32 bit and 64 bit versions of Windows, with the exception of Windows CE. In addition, we have to know that Cygwin is not a way to run native Linux applications on Windows. For this purpose, applications have to be rebuilt from source to run on Windows. Cygwin is released under the GNU General Public License and it is free software. It is maintained by employees of Red Hat, NetApp and many other volunteers. We need to use Cygwin, since it provides the basic development environment for TinyOS platform. In addition, Cygwin is required to develop applications for Tmote Sky hardware module (the hardware that we have used in our

system).

3.1.4 J2SE 1.4

Java Platform, Standard Edition (Java SE) provides facility to develop and deploy Java applications on desktops and servers, as well as embedded and real time environments [38]. In practical terms, Java SE consists of a virtual machine, which must be used to run Java programs, together with a set of libraries (or packages) needed to allow the use of file systems, networks, graphical interfaces, and so on, from within those programs. We have used J2SE 1.4 for developing the end user application and gateway.

Comparing J2SE 1.3 and 1.4, J2SE 1.4 adds new features and functionality, enhanced performance and scalability, and improved reliability and serviceability. Even though, there are newer releases of J2SE such as 1.5 or 1.6, we need to use 1.4 version, because the TinyOS tools have been only tested on the Java 2 Platform, Standard Edition v 1.4.2.

3.1.5 MySQL server 5.2

MySQL is a Relational Database Management System (RDBMS) [55]. MySQL is written in C and C++. The program runs as a server providing multi-user access to a number of databases. The MySQL database has become the world's most popular open source database because of its consistent fast performance,

high reliability and ease of use. MySQL runs on more than 20 platforms including Linux, Windows. It has distinguishing features that other RDBMS softwares do not have such as commit grouping, by which it gathers multiple transactions from multiple connections together to increase the number of commits per second. We have used MySQL server 5.2 in our system for the purposes of efficient data storage and retrieval.

3.1.6 UML

The Unified Modeling Language (UML) is a graphical language for visualizing, specifying and constructing the artifacts of a software-intensive system [11]. UML offers a standard way to write a system's blueprints, including conceptual models such as business processes and system functions as well as concrete models such as programming language statements, database schema, and reusable software components. UML combines the best practices from data modeling concepts such as entity relationship diagrams, business modeling (work flow), object modeling and component modeling. We have used UML to design the end user application and gateway.

3.2 System Architecture

Our system consists of three main subsystems, namely the wireless sensor network, gateway/server and end user application. In the wireless sensor network, motes are

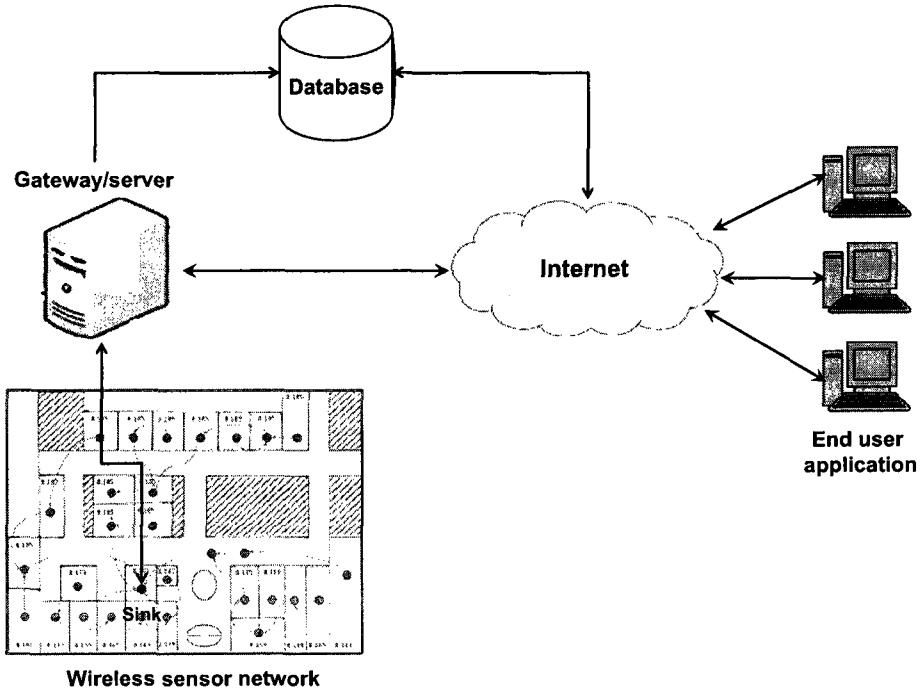


Figure 1: Automated Building Monitoring system by wireless sensor network architecture

responsible for collecting data about the climate and lamp status (room occupancy) in the rooms and sending it to the sink by multi-hop communication. The sink forwards data to the gateway through the USB port. The gateway/server acts as a server and forwards data received from the sink to the end user applications. The gateway/server also archives the data in the database. The end user application interprets the data for different purposes such as updating topology visualization of the network and motes status, etc. The end user application also can retrieve the data from the database for analysis. Figure 1 shows the architecture of our system.

3.3 Wireless sensor network

In this section, first we describe the platform on which the application is tested for building monitoring. Second, we explain the motes application design. Finally, we break down each main component and functioning part of the application.

3.3.1 Platform

The mote that we have used for implementing the wireless sensor network part of our system is Tmote Sky module. Tmote Sky is produced by Moteiv incorporation. The selection criteria for this platform are explained in section 2.2. Here, we explain more the hardware and features of this module.

Tmote Sky uses standards such as USB and IEEE 802.15.4. It has also integrated humidity, temperature and light sensors with flexible interconnection with peripherals. Its microcontroller is MSP430 (10k RAM, 48k Flash) with integrated ADC, DAC, Supply Voltage Supervisor, and DMA Controller. Tmote Sky uses on board antenna with 50m range indoors / 125m range outdoors for communication with other motes. In addition, it has low current consumption and fast wakeup from sleep. It runs over TinyOS operating system and applications developed by NesC programming language [36]. Figure 2 shows the Tmote Sky hardware.

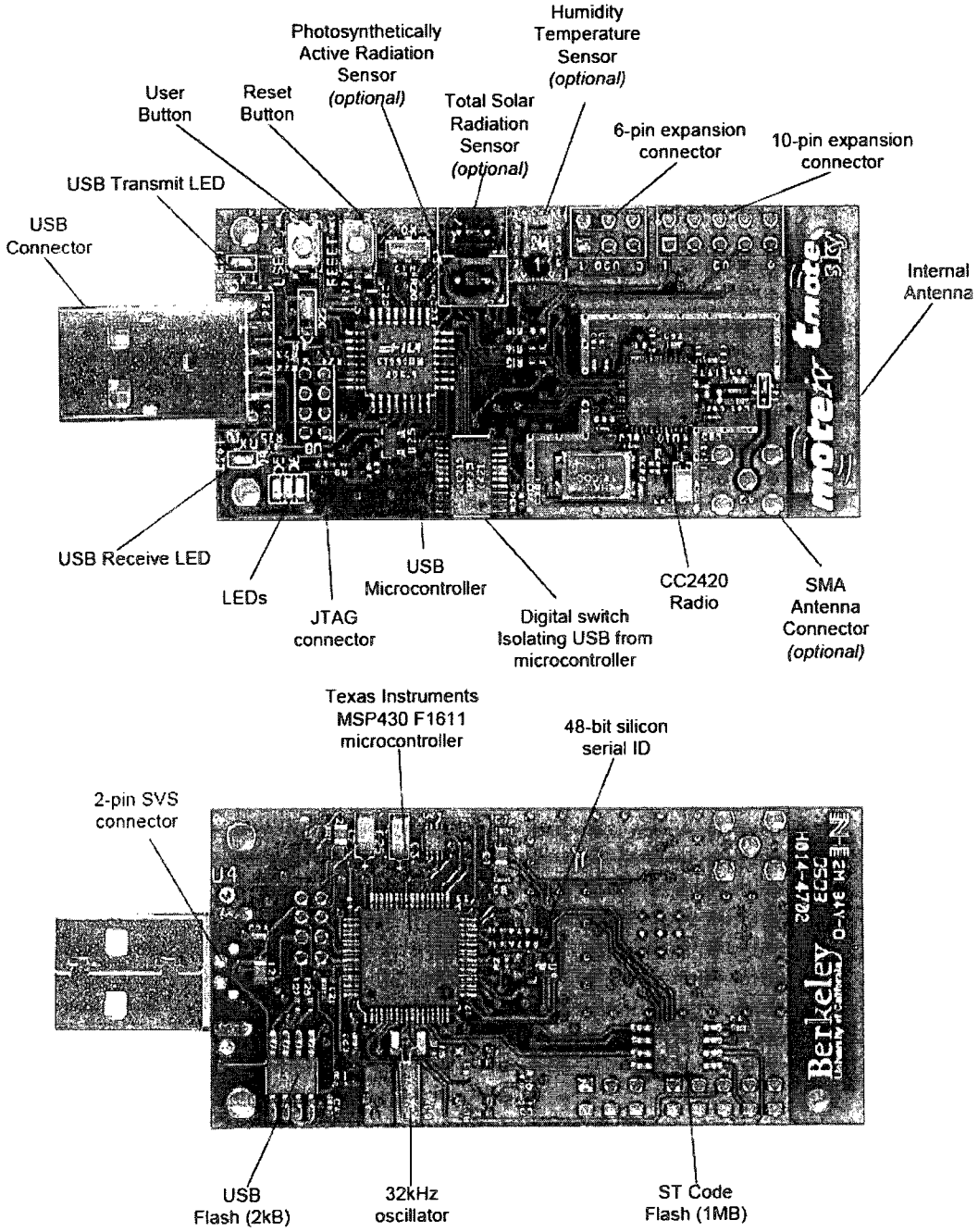


Figure 2: Front and back side of Tmote Sky module

Operating condition	MIN	NOM	MAX	UNIT
Supply voltage	2.1		3.6 V	V
Supply voltage during flash mem. programming	2.7		3.6	V
Operating free air temperature	-40		85	°C
Current Consumption: MCU on, Radio RX		21800	23000	μA
Current Consumption: MCU on, Radio TX		19500	21000	μA
Current Consumption: MCU on, Radio off		1800	2400	μA
Current Consumption: MCU idle, Radio off		54.5	1200	μA
Current Consumption: MCU standby		5.1	21.0	μA

Table 2: Power consumption of Tmote Sky

Power

Tmote Sky is powered by two AA batteries. AA batteries can be used in the operating range of 2.1 to 3.6V DC. If the Tmote Sky module is plugged into the USB port for programming or communication, it will receive power from the host computer. The mote operating voltage when attached to USB is 3V [36]. When Tmote Sky is used as sink, it has to be connected to the work station, since a Tmote that is always attached to a USB port does not need a battery pack and can be always on. The power consumption of the Tmote Sky in different operating conditions is shown in Table 2. As we can see in this table, the power consumption of Tmote Sky is in its highest value when the radio is in receive or transmit state. Therefore for energy conservation, we use low duty cycle of 5%. It means that the radio is on 5% of the time in every 2 seconds for transmitting and receiving.

Radio (IEEE 802.15.4)

Tmote Sky uses the Chipcon CC2420 [83] radio for wireless communications. The CC2420 is an IEEE 802.15.4 compliant radio providing the PHY and some MAC functions. With sensitivity exceeding the IEEE 802.15.4 specification and low power operation, the CC2420 provides reliable wireless communication [27, 33]. The CC2420 is controlled by the TI MSP430 microcontroller through the SPI port and a series of digital I/O lines and interrupts. The radio can be turned off by the microcontroller for low power duty cycled operation [36].

The CC2420 provides a digital received signal strength indicator (RSSI) that may be read any time. Additionally, on each packet reception, the CC2420 samples the first eight chips, calculates the error rate, and produces a link quality indication (LQI) value with each received packet. We use LQI for routing purposes. Routing algorithm is described in Subsection 3.3.5.

Valid channels of the IEEE 802.15.4 [10] radio transmission standard are 11 through 26. The channel frequencies are calculated by Equation 1. Therefore, the frequency would be from 2.4 GHz to 2.4835 GHz. In buildings which are using IEEE 802.11 for WLAN purposes, there is a possibility of interference with IEEE 808.15.4. For avoiding this problem, we use last channel of the IEEE 802.15.4 which is using 2.480 GHz frequency. From Figure 3, we can see 2.480 GHz is out of the frequency range of IEEE 802.11 channels enough to avoid interference.

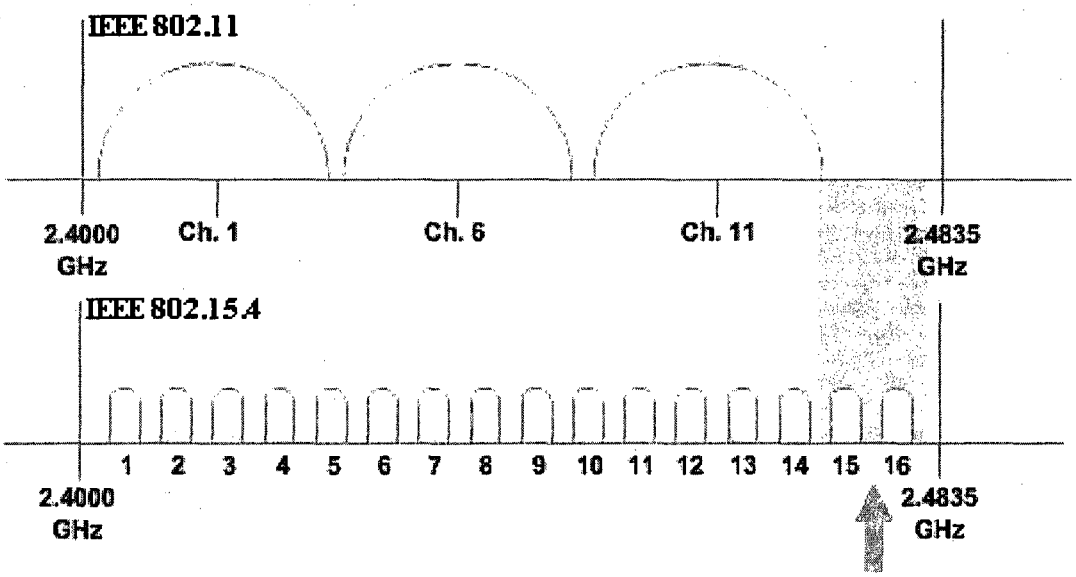


Figure 3: Channel comparisons between IEEE 802.11 and IEEE 802.15.4

$$Freq = 2405 + 5(k - 11)\ MHz\ for\ k = 11, 12...26 \tag{1}$$

In addition, power index for the radio module installed on Tmote sky is from 1 to 31. The input value is simply an arbitrary index that is programmed into the CC2420 registers. The output power is set by programming the power amplifier. The valid values are 1 through 31 with power of 1 equal to -25dBm and 31 equal to max power (0dBm) [16].

Sensors

Tmote Sky modules have the following sensors on board: Sensirion, Hamamatsu Photo synthetically Active Radiation (PAR) and Hamamatsu Total Solar Radiation (TSR) [36].

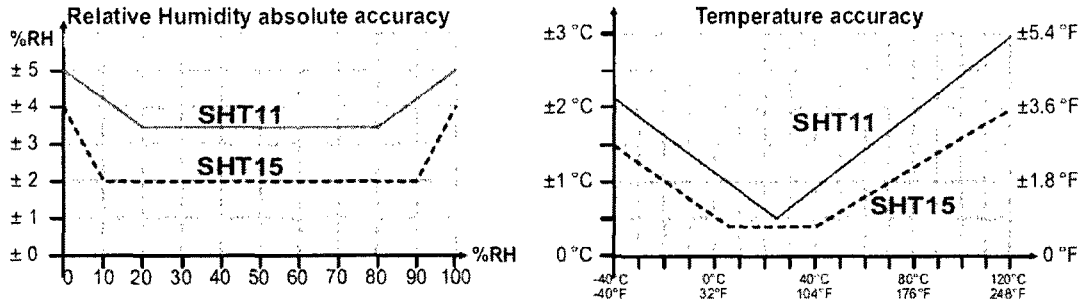


Figure 4: Accuracy of Sensirion relative humidity and temperature sensors

Sensirion sensor: Humidity and temperature sensor is manufactured by Sensirion AG. SHT11 and SHT15 models are common sensors to be directly mounted on the Tmote Sky module in the U3 component position. SHT11/SHT15 sensors are calibrated and produce a digital output. The calibration coefficients are stored in the sensors on board EEPROM [36]. The difference between SHT11 and SHT15 model is that SHT15 produces higher accuracy readings as shown in Figure 4 [72]. On Tmote Sky modules which are used in our system, SHT11 model is mounted. The sensor reading is produced using a CMOS process and is coupled with a 14-bit A/D converter (Analogue to Digital converter) [72].

In order to be readable, SHT11 Sensirion sensor readings have to be changed. The output for temperature is 14-bit value that can be converted to degrees Celsius (°C) using the Equation 2 in which SOt is the raw output [16]. The accuracy of SHT11 for measuring temperature at 25°C is ±0.4. The range of its measurement is from -40 to 123.8 °C [16, 72].

$$Temperature = -39.60 + 0.01 * SOt \quad (2)$$

For relative humidity measurement, the output is a 12-bit value that is not temperature compensated. The SI unit value for humidity can be calculated from Equation 3 where SOrh is the raw output of the relative humidity sensor [16, 72].

$$Humidity = -4 + 0.0405 * SOrh + (-2.8 * 10^{-6}) * (SOrh^2) \quad (3)$$

By using the calculated humidity from Equation 3 and calculated temperature from Equation 2, the humidity measurement can be corrected with temperature compensation in Equation 4 [16, 72]. In Equation 4, Tc is the temperature measured in °C from Equation 2, SOrh is the raw output of the relative humidity sensor, and Humidity is the uncompensated value calculated in Equation 3.

$$Humiditytrue = (Tc - 25) * (0.01 + 0.00008 * SOrh) + Humidity \quad (4)$$

In Table 3, the detailed performance specification of the SHT11 sensor is listed [72].

Hamamatsu Photo-synthetically Active Radiation (PAR) and Total Solar Radiation (TSR) sensors These two sensors are used for measuring the

Parameter	MIN	TYP	MAX	Units
Humidity				
Resolution	0.5	0.03	0.03	%RH
	8	12	12	Bit
Range	0		100	%RH
Temperature				
Resolution	0.04	0.01	0.01	°C
	0.07	0.02	0.02	°F
	12	14	14	bit
Range	-40		123.8	°C
	-40		254.9	°F

Table 3: Sensirion relative humidity and temperature performance specifications

light. It takes about two minutes for each sensor to be calibrated and sense the right data. The motes that we have used in our system are equipped with these light photo-diodes. The diodes are S1087 for sensing Photo-synthetically Active Radiation (PAR), which is the entire visible spectrum and S1087-01 for sensing the Total Solar Radiation (TSR), which is the entire visible spectrum expanding to infrared. Figure 5 shows the photo sensitivity of the light sensors on Tmote Sky [61].

The TSR and PAR sensor readings are also transfered by using the micro-controllers 12-bit ADC with voltage of 1.5V. The photo-diodes create a current through a 100kOhm resistor. By calculating the raw voltage and converting this voltage into the current using Equation 5 in which Vsensor is the raw voltage (1.5V), the current created by photo-diodes is calculated.

$$I = \frac{Vsensor}{100,000} \tag{5}$$

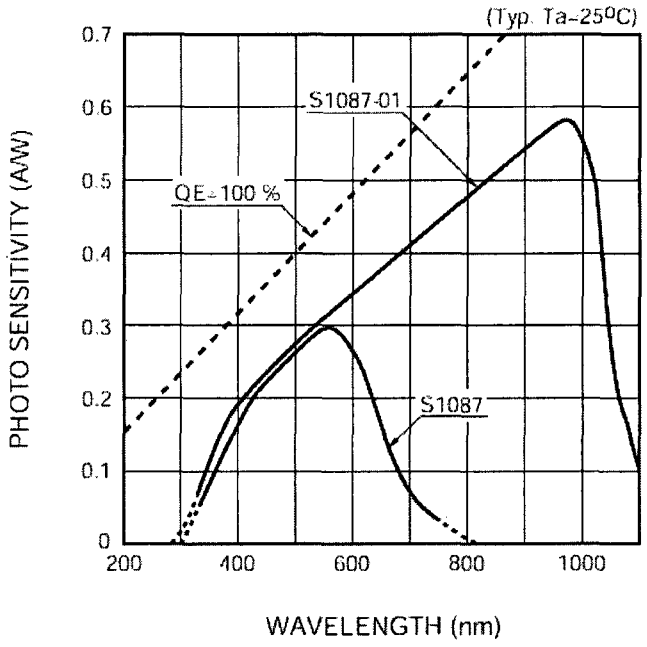


Figure 5: Photo sensitivity of the light sensors on Tmote Sky

S1087 light sensors datasheet includes a curve for converting the photo-diode's current into incident light level (lux or lx) [61]. The lux is the metric unit of illuminance [59] for measuring the amount of light that falls on an object. Lux is the European unit equivalent of the British foot-candle (or lumen). Specifically, one lux is equal to the amount of light that falls on a one-square-meter surface which is one meter away from a single candle. Ten lux equals the amount of light produced by ten candles one meter away [1]. Table 4, shows the equivalence of real world examples to different lux values [69].

The short circuit current linearity for S1087 and S1087-01 are shown in Figure 6. For calculating the sensed lux by S1087 sensor (sensing Photo-synthetically Active Radiation (PAR), which is the entire visible spectrum), we use Equation 6.

Illuminance	Example
0.00001 lux	Light from the brightest star(Sirius)
0.0001 lux	Total starlight, overcast sky
0.002 lux	Moonless clear night sky with airglow
0.01 lux	Quarter moon
0.27 lux	Full moon on a clear night
1 lux	Full moon overhead at tropical latitudes
3.4 lux	Dark limit of civil twilight under a clear sky
50 lux	Family living room
80 lux	Hallway/toilet
100 lux	Very dark overcast day
320 lux	Recommended office lighting (Australia)
400 lux	Sunrise or sunset on a clear day. Well-lit office area
500 lux	Recommended office lighting (Europe)
1000 lux	Overcast day or typical TV studio lighting
10000 to 25,000 lux	Full daylight (not direct sun)
32000 to 130000 lux	Direct sunlight

Table 4: Equivalence of real world examples to different lux values

For S1087-01 sensor (sensing the Total Solar Radiation (TSR), which is the entire visible spectrum expanded to infrared), we use Equation 7 to calculate the sensed lux. In both equations, I is calculated from Equation 5.

$$Lux\ of\ S1087 = 0.625 * 1^{-6} * I * 1000 \tag{6}$$

$$Lux\ of\ S1087 - 01 = 0.769 * 1^{-5} * I * 1000 \tag{7}$$

3.3.2 Design

We have used TinyOS 1.2 operating system and NesC programming language in Cygwin environment for developing the code for the motes of the wireless sensor

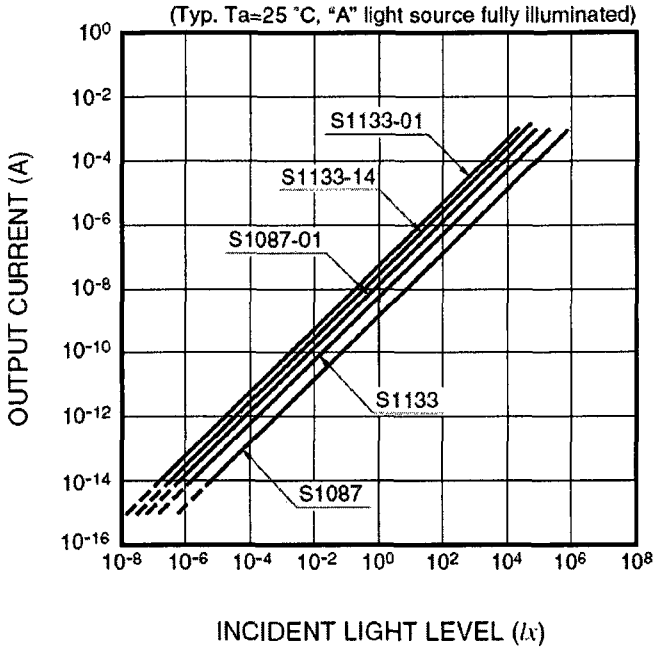


Figure 6: Short circuit current linearity

network of our system. The application that we have developed consists of many components linked together to form an executable. A component provides and uses interfaces, which are the only point of access to the component. An interface declares two sets of functions called commands and events. Commands are functions that the component providing the interface should implement. Events are functions that the component using the interface should implement. Events are the responses to the commands. For instance, when *MultiHop* component uses *SendMessages* interface to use Send command of *LinkLayer* component for sending a message, as a result of the completion of the function, event of *SendDone* in *MultiHop* component through *SendMessage* interface will be called back. This

means that the interfaces are bidirectional. However, in graphical view of the components relations, the direction of the interfaces usage is shown. For example, if component A wants to use commands of the component B by interface X, an arrow from component A to B shows their relation and representing interface X.

In addition, there are two kinds of components: module and configuration. Modules provide application code, implementing one or more interfaces. Configurations are used to assemble other components together, connecting interfaces used by components to interfaces provided by others. This is called wiring. Every nesC application is described by a top-level configuration that wires together the components inside. However, in graphical view of components relations just the module components would be mentioned.

Figure 7 shows the graphical view of components relations of our motes application. In this figure, we have merged all the interfaces between two components to one interface, omitted the names of the interfaces and just kept the main important components of the application to be more understandable and clear.

In the motes application, main component is the system component, which is responsible for starting all other components. The two main components of our application are *BMappl* and *NetSync*. *BMappl* component is using interfaces to connect to other components such as sensors, multi-hop communication components etc. Main tasks of *BMappl* component are collecting data from sensors every 30 seconds, calculating lamp status and generating messages to be sent to

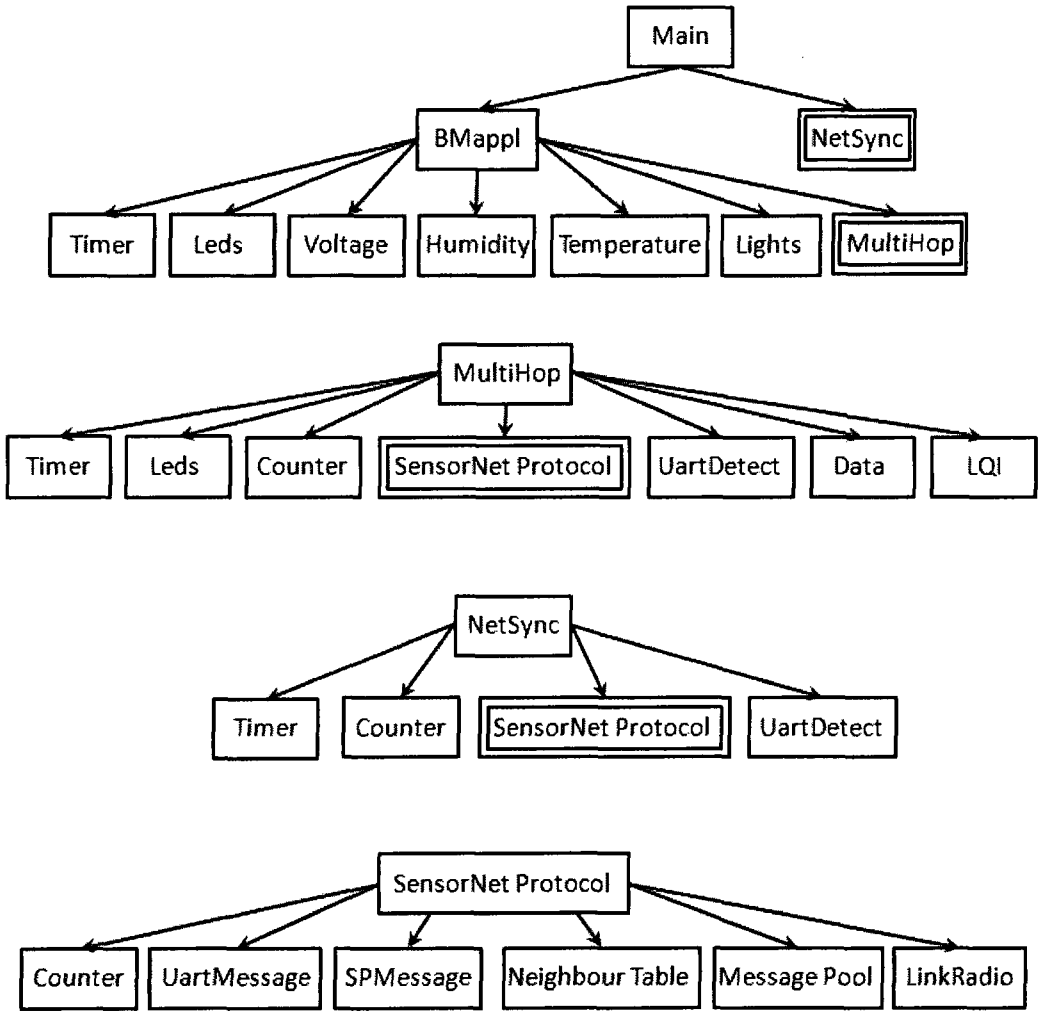


Figure 7: Graphical veiw of components relations of the motes application

the sink. This component sends the messages to the sink by forwarding them to the *MultiHop* component. Another main component is *NetSync*, which is responsible for keeping the whole network synchronized for waking up and going to sleep. *NetSync* component uses different components such as *UartDetect*, Timer and Counter to perform the synchronization. Both *MultiHop* and *NetSync* components use *SensorNetProtocol* component. *SensorNetProtocol* is a unifying link abstraction for running network protocols over a variety of link layer and physical layer technologies without changing network protocol implementation [63]. Each of the components is explained in detail in the rest of this section.

3.3.3 Sensing functions

As we explained in Subsection 3.3.1, there are three sensors mounted on Tmote Sky modules: SHT11 Sensirion sensor for sensing temperature and humidity, S1087-01 Hamamatsu sensor for sensing TSR, and S1087 Hamamatsu sensor for sensing PAR. However, we need to use two components in TinyOS for using these sensors. *HamamatsuC* component is used for S1087 and S1087-01 sensors and *HumidityC* component is used for SHT11 sensor.

We need to use interfaces wired to the sensors component to get the analogue readings from the sensors and convert them to digital one. For this purpose, we use ADC (analogue-to-digital converter) interface to connect to the sensor components. One ADC interface is defined for each sensor reading as follows:

```
interface ADC as Temperature;
interface ADC as Humidity;
interface ADC as TSR;
interface ADC as PAR;
```

Temperature interface is used for getting the sensed temperature. *Humidity* interface is used for measuring the humidity. *TSR* and *PAR* interfaces are used for measuring the light. TSR and PAR differences are explained in Subsection 3.3.1. For getting data from the sensors, *ADC* interfaces are wired to appropriate interfaces of the sensors component. *Temperature* and *Humidity* interfaces are wired to interfaces in *HumidityC* component and *TSR* and *PAR* interfaces are wired to interfaces in *HamamatsuC* component. In addition, more interfaces are used for controlling purposes and error detection of sensors readings. Examples of wiring between interfaces are as follows:

```
Impl.Humidity -> HumidityC.Humidity;
Impl.HumidityError -> HumidityC.HumidityError;
Impl.PAR -> HamamatsuC.PAR;
```

After wiring the ADC and controlling interfaces to the appropriate interfaces of the sensors component, the timer is defined for determining the intervals in which sensors have to be sampled. The timer for sensing purpose is set to be fired every 30 seconds. The *TimerC* component is used in our application for this purpose. In

the other words, *TimerC* component calls Timer.fired command every 30 seconds to collect the sensor readings. After the timer is fired, each ADC interface is called to collect the reading. Then, sensor readings will be processed and forwarded to *MultiHop* component to be sent to the sink.

In addition, we need to collect the current voltage of the power supply of each mote. The current voltage of the power supply is used by the end user application to calculate remaining lifetime of the motes. *InternalVolatge* interface is used for connecting to *VoltageC* component, which returns the current supply voltage. This value is collected every 30 seconds. For firing the event of reading voltage, we have used the same timer that is used for the other sensors' reading. The collected supply voltage is forwarded to *MultiHop* component with other sensors reading to be sent to the sink.

As we explained in Subsection 3.3.1, the sensors' reading are not in metric units and they have to be calculated to be understandable. We do not calculate the metric units of the sensors reading in the motes for conserving energy. For sending the raw or calculated sensors reading, the same number of bytes is necessary in every message to be sent to the sink. Therefore, by calculating the sensors' readings in the motes, not only we do not lower the routing overhead, but also we use the motes energy to calculate sensors reading in metric units.

Finally, our application is used for safety as well. All end users are alerted in case of detection of any light with density or out of visual spectrum such as

Sensors reading	Min Raw data - Metric unit	Max Raw data - Metric unit
Temperature	5,460 - 15°C	8,354 - 40°C
Humidity	355 - 10%RH	2,703 - 85%RH
TSR	0 - $0lx$	88,776 - 25,000lx
PAR	0 - $0lx$	10,923 - 25,000lx

Table 5: Predefined thresholds of sensor readings for alerting the end user

infrared, and change in the climate conditions of the building such as temperature drop or rise. The process of alerting can be performed by checking sensors' reading to make sure they are not out the predefined threshold before sending to the sink. The thresholds are defined before programming the motes, then written in the code of the motes. In case of sensing very high or low temperature, very high or low humidity, or light with high lux, the motes send the messages every 5 seconds instead of 30 seconds. The messages are sent more frequently for increasing the delivery ratio and letting the end user have the up-to-dated status of the event. The predefined thresholds that we have use in our application are mentioned in Table 5.

3.3.4 Lamp status (room occupancy)

As we explained in Section 1.2, we are interested in the lamp status (on/off) and room occupancy of each room. We assumed that the room is occupied when the lamps of the room are on and the room is empty when the lamps are off. In the motes application, lamp status is calculated and sent to the sink along with the sensor readings every 30 seconds. Each time for calculating the lamp status, 100

samples of light sensors are collected. Therefore, it is more energy efficient to calculate the lamp status in the motes than sending all of the 100 samples to the sink. The 100 samples are collected with 10 milliseconds intervals. The collection starts one second before sending each message to the sink for having the lamp status ready with other sensor readings.

For collecting the 100 samples, we defined *TimerSenseLight* timer, which gets fired 29 seconds after the timer for the sensors readings is fired. When the *TimerSenseLight* is fired, 100 samples of TSR and PAR light sensors are collected in one second and saved in the mote's memory. Then, *calculateLampStat()* method is called and lamp status is calculated. Lamp status is sent to the *MultiHop* component along with other sensor readings for preparing of the message to be sent to the sink.

Lamp status is calculated based on the fact that power supply of most of the lamps in offices is Alternating Current (AC). AC flows one way, then the other way, continually reversing direction. An AC voltage is continually changing between positive (+) and negative (-). The rate of changing direction is called the frequency of the AC and it is measured in hertz (Hz) which is the number of forwards-backwards cycles per second. AC power in Canada has a frequency of 60Hz [9], meaning that electrical signal of AC power take 60 cycles in one second. The time period for the electrical signal of AC power is the time taken for the signal to complete one cycle. Figure 8 shows an electrical signal of AC power and

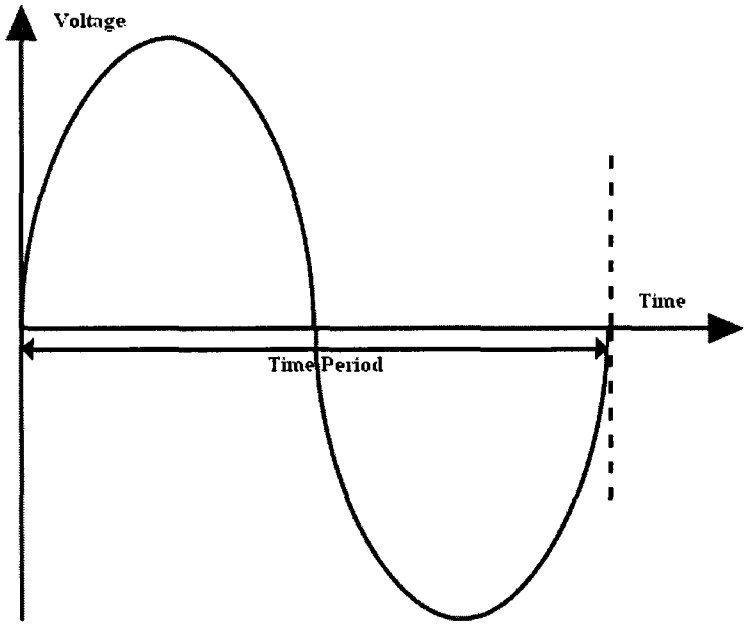


Figure 8: Voltage-time graph of an AC power electrical signal

its time period. The time period for AC power in Canada is calculated by Equation 8 to be 16.6 milliseconds.

$$Time\ period = \frac{1}{Frequency} \tag{8}$$

Therefore, the lamps which are using AC power in Canada flicker 60 times in one second. The light generated by lamps are going up and down due to the nature of AC power. When the electrical signal of AC power reaches its highest peak, the lamps are acting accordingly and they generate their highest brightness and when the electrical signal reaches zero, the lamps are generating no light. However, the persistence of human vision prevents the light to appear flickering as long as the light flickering rate is fast enough (greater than 20 flickering per second is good if

the human vision can tolerate some flickers, but generating flickering with rate of 60 per second avoids any appearance of intensity flicker [78]).

As we explained, the time period of AC power electrical signal is 16.6 milliseconds. Thus, the lamps take 16.6 milliseconds to complete one cycle of flickering. Therefore, we use light sensors to sense light of the lamps every 10 milliseconds for a period of 1 second to detect the flickering of the light. The lamps are on when the light is flickering and the lamps are off when the light is steady in a short period of time. In the other words, we detect the status of the lamps (on/off) in every room equipped with any kind of lighting system as long as they use AC power. The system is therefore able to detect the lamp status in the rooms with windows facing outside (having daylight) as long as light sensors are close enough to the lamps (less than 2 meters) and they are placed out of direct sunlight.

Moreover, we first tried to detect the lamps status by monitoring the changes in the level of brightness in the room. This method was working well for the rooms without the daylight, since the changes in the level of the brightness in such rooms are very distinguished and limited to two states. The lamps are either switched on or off. In each state, changes in the level of brightness are very high and unique in such a way that the level of brightness drops very low sharply when the lamps get switched off and it rises very sharply when the lamps get switched on. Figure 9 shows examples of changes in the level of brightness in the rooms without daylight. However, it is a different issue for the rooms with daylight. Figure 10 shows an

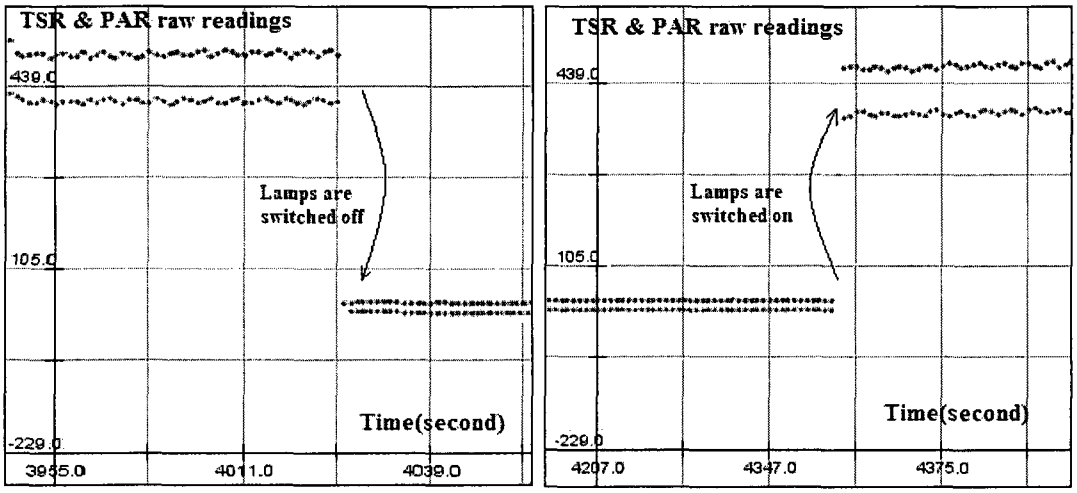


Figure 9: Changes of TSR and PAR raw readings when lamps are switched on or off in the rooms without daylight

example of changes in the level of brightness in different states in the rooms with daylight. After several testings and observations, we figured out that there is no specific pattern applicable to such cases.

During the tests, we found out that when the lamps are on in the room, the light sensors can sense the light flickers as long as light sensors are close enough to the lamps (less than 2 meters) and they are out of direct sunlight. However, the light in the rooms with daylight is steady in very short periods of time when the lamps are off. Figure 11 shows an example of light sensor readings in the room with daylight and switched off lamps. From this figure, we can see that even though the overall light in the room is increasing, but in small periods of time the differences in sensed light is one or two units. Figure 12 shows an example of light sensor readings in the room with daylight and switched on lamps. As we

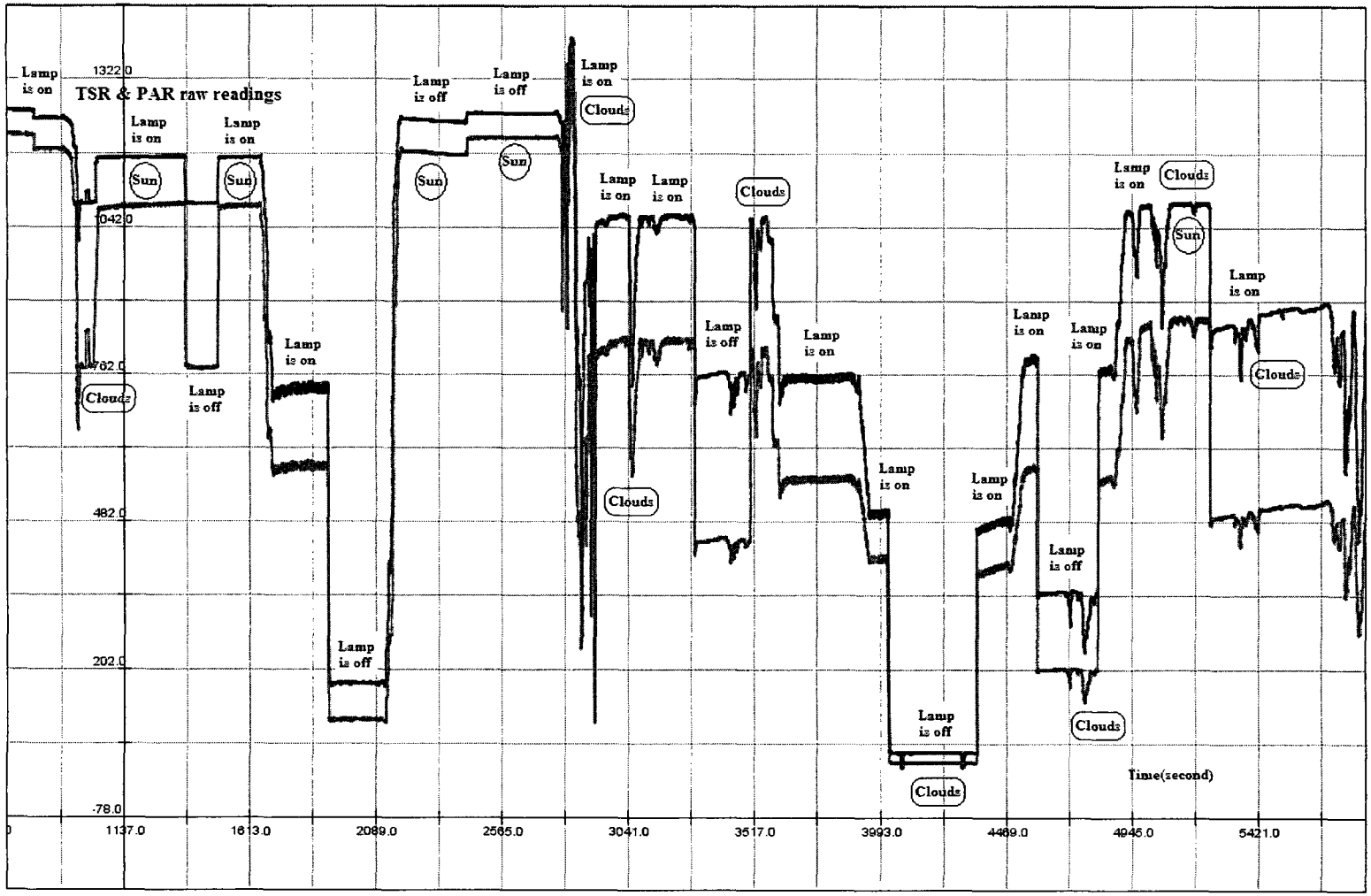


Figure 10: Changes of TSR and PAR raw readings when lamp is switched on or off during variable cloudy day in period of one hour in the room with daylight

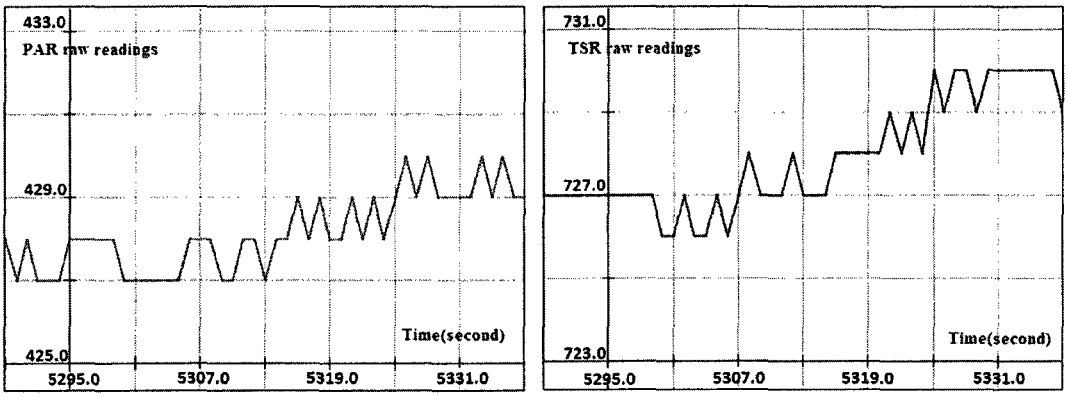


Figure 11: Changes of TSR and PAR raw readings when the light in the room is from Sun only

mentioned before, this figure shows the light from lamps in a short period differs between 3 to 12 units. Therefore, we calculate the lamp status by collecting 100 samples of light sensors with intervals of 10 milliseconds in 1 second. Then, we check the differences of each two subsequent sensors readings. If the difference is from 0 to 3, we add one to the *countOFF* counter and if the difference is from 4 to 12, we add one to *countON* counter. Whenever any of the counters reaches 5, we change the lamp status accordingly and set both counters to 0.

3.3.5 Routing algorithm

The routing algorithm (*MultiHop* component) of our application is based on the many-to-one data-collection scenario, since our application is classified under data gathering and periodic reporting class as we explained in Section 2.1.2. The used approach is to build one collection tree rooted at the sink. When a node has data to be collected, it sends the data up the tree. Also, a node forwards the

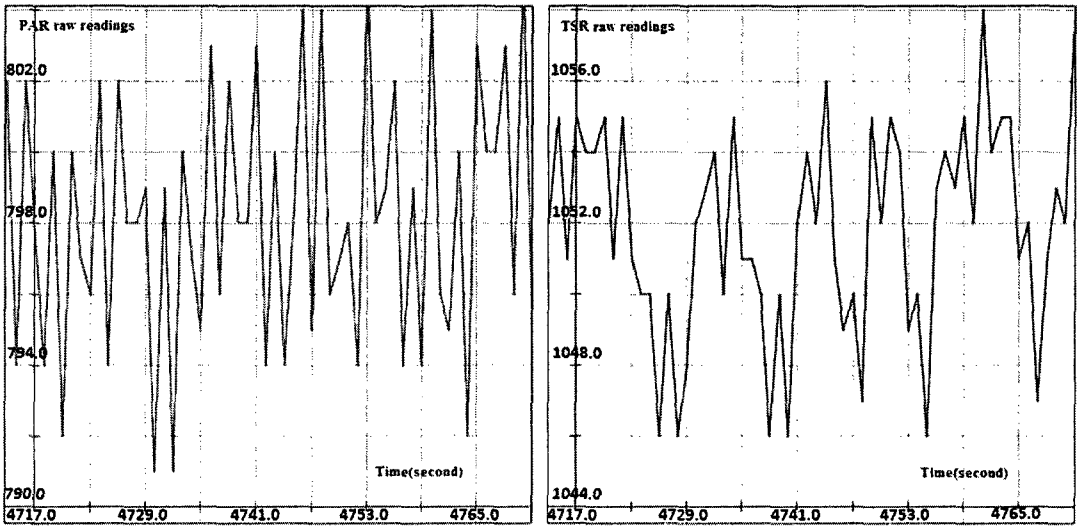


Figure 12: Changes of TSR and PAR raw readings when the light in the room is from both Sun and the lamps

collected data that is sent by other nodes. Messages are inspected as they go by, to suppress redundant transmissions and to avoid loops. As we mentioned in Section 2.3, in our system, messages are not inspected for data aggregation, since the collected data in our system is not redundant. The reason for not having redundant data in our system is that there is one mote in each room of the building and it makes all data collected from the motes independent of the others. We placed one mote in each room due to the small sizes of the rooms. Therefore, by using data aggregation, not only is the forwarded data not reduced but also, we have more in mote processing and delay in the network. Moreover, data query is not applicable in our system because of the class of data gathering and periodic reporting in which our application is classified. Thus, there is no need to query any part of the network to get data regarding any specific event.

MultiHop routing protocol chooses a parent based on the best link quality to the root of the collection tree. In this implementation, we have used additive link qualities, where zero represents a perfect link. A parent's quality is its advertised value, sent periodically via route update messages, plus the quality of the link between parent and child (lower values are better). The sink in our network is identified either by its id which is zero or by its connection to the PC. The sink's quality advertised to the neighbors is set to zero. *MultiHop* uses Link Quality Indication (LQI), which is a feature of the CC2420 radio with IEEE802.15.4 standard.

The IEEE802.15.4 standard enables the measurement of link quality between neighboring nodes in the network. This measurement is in the form of a Link Quality Indicator (LQI) value reported with each received packet. By averaging over several LQI values, an estimation of the link quality is obtained and consequently, an estimation of the probability of successful transmission is available to the *MultiHop* routing algorithm. The LQI measurement is a characterization of the strength and/or quality of a received packet, as defined by [27].

Figure 13 shows an example of selecting best route by the motes to the sink using the MultiHop routing algorithm. In the first step, the sink (mote 0) advertises link quality with value of zero to its neighbors. In step two, motes 2, 3 and 4 select the sink as their parent and set the value of their link quality to the sink (e.g., link quality of mote 2 to mote 0 is set to value 1). In step three, motes 2,3 and 4

advertises to its one-hop neighbors the route update message which has the parent link quality plus the link quality from themselves to their parent (e.g., mote 2 advertises the value of 1, that is, the sum of its parent link quality, which is 0 and the link quality from itself to its parent, which is 1). In step four, motes 5,6,7 and 8 select a mote with lowest advertised link quality as their parent (e.g., mote 6 selects mote 3 instead of 2 since the advertised value from mote 3 is less than the mote 2). Step five shows that whenever there is a tie between the advertised values, the mote with lower id is selected as parent (e.g., the advertised value from mote 7 and 8 to mote 9 are the lowest and both are the same, which is 4, therefore mote 9 selects mote 7 as its parent). In step six, the dashed lines show the two alternate parents that have been selected by mote 9.

MultiHop uses *Sensornet Protocol* (SP) as the underlying layer. SP provides shared neighbor management and a message pool in order to let multiple routing algorithms run over different link layers together. We explained SP in Subsection 3.3.7. *MultiHop* sends two kinds of traffic by using the *SPC* component which is the implementation of SP: route update beacons it broadcasts, and data messages it unicasts to the currently selected parent. The broadcast messages are sent through a unicast round-robin emulation. If the neighbor table in SP has no good potential parents, *MultiHop* requests SP to find new neighbors using the *SPNeighbor* interface. The find command maps to MAC layer 15.4's scan functionality to repopulate the neighbor table. In our implementation, the neighbor table keeps

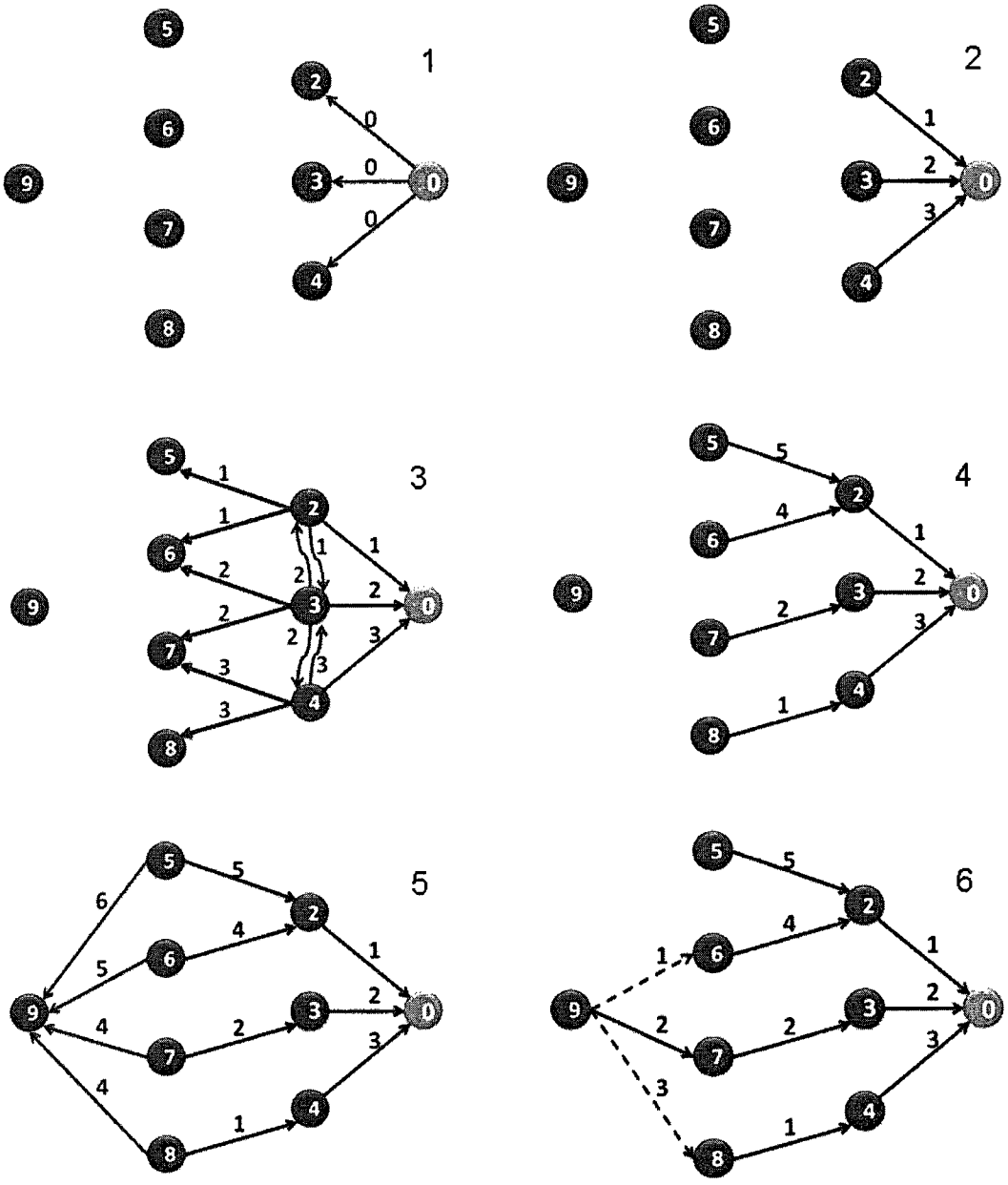


Figure 13: An example of selecting best route by the motes to the sink using the MultiHop routing algorithm

the information of at most three neighbors.

Given the limited states that motes can store and general need for distributed tree building algorithms, the *MultiHop* collection routing protocol encounters several challenges. The following are the challenges addressed in *MultiHop* routing algorithm:

Loop detection: Routing loops are problems that can happen in the network. Routing loops generally occur when a node chooses a new route that has a significantly higher link quality than its old one, perhaps in response to losing connectivity with a candidate parent and also the new route includes a node that was a descendant. For many-to-one routing over relatively stationary sensor networks, we believe that it is better to use simple mechanisms to avoid loop formation and to break cycles when they are detected, rather than to employ heavy weight protocols with inter-nodal coordination.

MultiHop addresses loops through two mechanisms. First, cycles can be detected quickly when a node in a loop originates a packet and observes it returning. Once a cycle is detected, it will be broken by discarding the parent by choosing a new one or becoming disjoint from the tree. The second mechanism is to use Time-To-Live (TTL) field in the data frame. We defined the TTL to be four times greater than the parent hop count to the sink. Whenever the message is forwarded by any mote, the value of TTL is reduced by one unit. The message will be dropped when the TTL becomes zero. Therefore, the messages cannot be stuck in the loop

forever.

Duplicate packet elimination: Duplicate packets can be created upon retransmission when the ACK is lost. Without duplicate packet elimination, the forwarded duplicates will possibly cause more retransmissions and more contention, beside wasting energy. This can have disastrous effects over multiple hops, as the duplication is exponential. For example, if each hop on average produces one duplicate, then on the first hop there will be two packets, on the second there will be four, on the third there will be eight and so on.

To avoid duplicate packets, the routing layer at the originating node appends the sender id and an originating sequence number in the routing header. To suppress the forwarding duplicate packets, each parent retains the most recent originator id and originating sequence number in child entries in the neighbor table.

Implementation

Figure 14 shows the graphical view of components relation of the *MultiHop* routing algorithm in our system. The implementation of *MultiHop* has the following major parts:

Collection interfaces: The motes can perform three different roles in collection: producer, snooper and consumer. Depending on their role, the motes use different interfaces to interact with the *MultiHop* routing algorithm component.

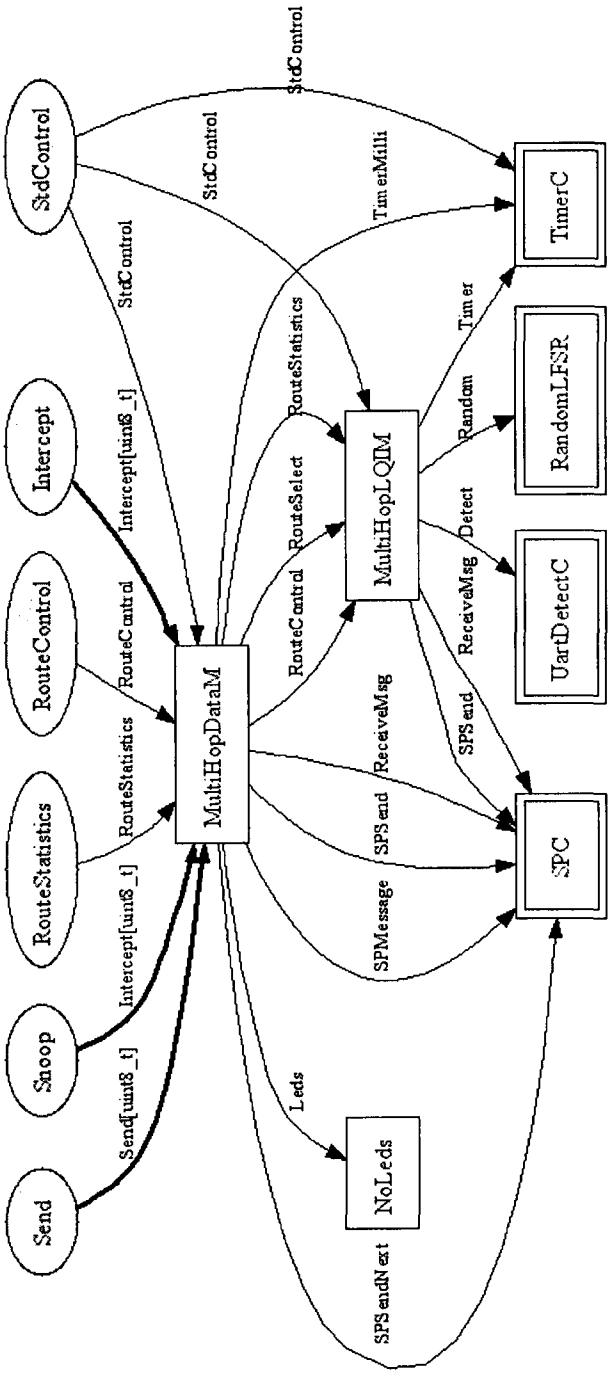


Figure 14: Graphical view of components relation of *MultiHop* component

The nodes that generate data to be sent to the root are producers. The producers use the send interface (*MultiHop.Send[AM_BMAPPLMSG]*) to send data to the root of the collection tree. The collection identifier is specified as a parameter to send during instantiation. The collection identifier is unique and used in the mote application and the end user application for identifying the application that collects the sent data. In the other words, identifier is used to distinguish different kinds of messages for data transfer or route update. One advantage of using SP as the under-layer of the routing algorithm is having different applications implemented in the motes for different purposes. As we explained in Subsection 3.3.2, two components of *NetSync* and *MultiHop* are implemented independently over the SP layer. Figure 7 shows the graphical view of the components relation of the mote's code and also the independent implementation of *NetSync* and *MultiHop* components. Each of the messages in the motes has its unique identifier. For instance, the identifier for data collected by *BMappl* is $AM\_BMAPPLMSG = 33$.

The motes that overhear messages in transit are snoopers. The snoopers use the receive interface (*MultiHop.Snoop[AM_BMAPPLMSG]*) to receive a snooped message. Intercept has a single event which is *Intercept.forward()*. A collection service in other routing algorithms signals this event when it receives a packet to forward. However, in our routing algorithm because of not having in mote processing, the routing algorithm calls this event automatically upon receiving a message to forward. This causes less delay to avoid the message to go to upper

level.

Root node (the sink) that receives data from the network is consumer. The sink uses the receive interface (*MultiHop.Intercept[AM_BMAPPLMSG]*) to receive a message delivered by collection and forward it to USB port connected to the PC. In *MultiHop* component, the *RootControl* interface configures whether a node is a root or not by checking if one of following factors are true, whether the mote has id number zero or the mote is connected to the PC. The connection and communication to the PC is handled by *UartDetectC* component.

Data messages: The data message frame is used by *MultiHop* component to send collected data to the sink. The data forwarded from the application layer is encapsulated in the data field of the data message. The data message has different fields mentioned in Table 6. In this table, *sourceaddr* is the id of the last mote that forwarded the message. *originaddr* is the id of the mote that collected the data. For instance, if mote1 sends its own collected data, both the *sourceaddr* and *originaddr* are 1. However, if mote1 forwards data message to mote4, the *sourceaddr* will be 1 and *originaddr* will be 4. *seqno* is the sequence number of messages sent from the source address. *originseqno* is the sequence number of messages forwarded by the mote. *ttl* is the time duration in which the message has lived. id is the type of the data message. data field is the collected data by application layer. The identifier of data messages is $AM\_MULTIHOPMSG = 8$.

Field	Size(bits)
sourceaddr	16
originaddr	16
seqno	16
originseqno	16
ttl	8
id	8
data(BMappl messages)	240
Whole size in bytes	40

Table 6: Data messages structure in *MultiHop* routing algorithm

***BMappl* messages:** Collected data in *BMappl* is saved in the *BMapplMsg* data structure. Then, *BMapplMsg* will be forwarded to the *MultiHop* component to be encapsulated in a data message frame. *BMapplMsg* structure is mentioned in Table 7. Most of the fields are self explanatory except the neighbor related fields. *neighborsize* field is the number of neighbors of the mote that their information is sent in this message. Each mote saves information of up to maximum eight neighbors since its radio neighborhood size is 8. However, *neighborsize* can be from one to maximum three in order to avoid very big messages. Having information about maximum three of the neighbors is enough to draw and analyze the connectivity status of the whole network and each mote. The two arrays of *neighbors[3]* and *quality[3]* have the id of the neighbors and quality of the links to those neighbors. The identifier for collected data in *BMapplMsg* is $AM\_BMAPPLMSG = 33$.

Route update beacons: Route update beacons are used by *MultiHop* component for updating its neighbor table. Beacons are sent every 30 seconds to single-hop neighbors. Table 8 shows the fields of the beacons. parent is the id of

Field	Size(bits)
seqno	32
data0Temp	16
data1Hum	16
data2TSR	16
data3PAR	16
data4LampStat	8
data5IVolt	16
parent	16
neighborsize	8
neighbors[3]	3*16
quality[3]	3*16
Whole size in bytes	30

Table 7: *BMappl* message structure in *MultiHop* routing algorithm

Field	Size(bits)
parent	16
cost	16
hopcount	16
Whole size in bytes	6

Table 8: Route update beacons structure in *MultiHop* routing algorithm

the mote itself. cost is the link quality of the route from the mote itself to the sink. *hopcount* is the hop count from the mote to the sink. The identifier of route update beacons is $AM\_BEACONMSG = 7$.

***MultiHopDataM* and *MultiHopLQIM* components:** *MultiHopDataM* module manages the data flow of messages, and uses SP to queue outgoing messages for transmission. This module uses link quality provided from *MultiHopLQIM* as well as network-level information to decide which neighbor is the next routing hop. *MultiHopLQIM* module is link estimator for *MultiHop* router. It assists *MultiHopDataM* in assigning routes and forwarding messages by using Link Quality

Indications (LQI).

***RouteStatistics* and *RouteControls* components:** Both components are used to keep track of routing information and make route selection decisions. When a Send component wants to send a packet from the application layer, it passes it to either *RouteStatistics* or *RouteControls* components for its routing information to be filled in. This way, the Send component is entirely unaware of the routing header structure.

3.3.6 Synchronization

The power consumption of the motes is in its maximum value when the radio transceiver is on. The power consumption of the Tmote Sky in different operating conditions is shown in Table 2. For energy conservation, we minimize the amount of time that the radio has to be on. The motes in our network transmit and receive for 100 milliseconds every two seconds. The ratio of the time in which the mote's radio transceiver is on to sum of the time in which the radio module is on or off is called the *duty cycle*. Therefore, the duty cycle of the radio module of the motes is 5%. In order to have an appropriate functionality in the network, all motes are synchronized together in such a way that they turn on and off their radio transceiver for transmitting and receiving at the same time.

In the rest of this section, we explain the calculation of the required duty cycle and the estimated lifetime of the motes. Then, we describe the *NetSync*

Factor	Value	Unit
Channel capacity	100	Msgs per second
Max network usage	90	%
Control messages interval	15	Seconds
Radio neighborhood size	8	
Data messages interval	30	Seconds
Number of the Motes	50	
Number of the sinks	1	

Table 9: Considered factors for calculating required duty cycle for the wireless sensor network.

component, which enables the synchronization.

Duty cycle and estimated lifetime

For calculating the required duty cycle, we considered different factors of the network, which are listed in Table 9. In this table, channel capacity is the maximum number of messages that the radio of Tmote Sky can transmit or receive per second. We considered the maximum network usage to be 90% and leave the rest for dropped packets. Control message interval is the time between sending the control messages such as route beacons. Radio neighborhood size is the maximum number of neighbors that the mote in our network can have. Data messages interval is the time between data collection by the motes.

Based on the factors mentioned in Table 9, first we estimate the *message load* for each mote. The message load is the frequency of transmitting and receiving data and controlling messages per second. The message load is calculated by the following equation:

$$Message\ load = f_1 + f_2$$

where f_1 is the frequency of control messages and f_2 is the frequency of data messages. f_1 is calculated as follows:

$$f_1 = \frac{Number\ of\ control\ messages}{Control\ messages\ interval}$$

The number of control messages, which includes synchronization and routing messages, is independent of the size of the network. f_2 is calculated as follows:

$$f_2 = \frac{Number\ of\ data\ messages}{Data\ messages\ interval}$$

The number of data messages is dependent on the size of the network. In the worst case scenario — the messages of all motes should be forwarded by one mote to the sink — if the number of the motes is N, the number of data messages to send and receive by one mote is 2N-1.

Then, we calculate the duty cycle as follows:

$$Duty\ cycle = \frac{Message\ load}{(Channel\ capacity)(Maximum\ network\ usage)}$$

where channel capacity is 100 messages per second and maximum network usage is considered 90 %.

Moreover, for calculating the lifetime of each mote, we use the power consumption information of Tmote Sky in Table 2. Even though the required duty cycle for our application is 5%, we calculate the lifetime of the motes in the network with three different duty cycles: 100%, 5% and the lowest 1%. Our network can run with 1% duty cycle if the data messages interval is changed to 360 seconds (6 minutes). In the network with 100% duty cycle, the motes are running in full power (100% duty cycle), meaning that their radio transceiver is always on and ready to transmit and receive. In the networks with 5% and 1% duty cycle, the motes are running in low power, meaning that their radio transceiver is on only in the 5% or 1% of the time. For this calculation, we consider 20mA for the active current of the motes in which its radio module is on and 10μA for the sleep current of the motes in which its radio module is off. In addition, we count the energy source as two Eveready AA Alkaline batteries with 2600 mAH (2600 milli-Ampere-Hour) [20]. The results of the calculation are shown in Table 10. The calculation of the mote's lifetime is done as follows:

$$Average\ current = (Active\ current)(Duty\ cycle) + (Sleep\ current)(1 - Duty\ cycle)$$

$$Life\ time\ of\ the\ motes = \frac{Batteries\ energy}{Average\ current\ usage}$$

Duty cycle	lifetime(Months / days)
1%	16.96 / 516
5%	3.53 / 107
100%	0.18 / 5

Table 10: Lifetime of the motes with different duty cycles

NetSync component

We used *NetSync* component developed by Moteiv Corporation [53] for network-wide synchronization of SP-enabled devices. *NetSync* enables and maintains network synchronization for devices running the SP link-layer abstraction (explained in Subsection 3.3.7). *NetSync* is based on Trickle [42], which is an algorithm for propagating and maintaining code updates in wireless sensor networks. Borrowing techniques from the epidemic/gossip, scalable multi-cast, and wireless broadcast literature, Trickle uses a polite gossip policy, where motes periodically broadcast a code summary to local neighbors but stay quiet if they have recently heard a summary identical to theirs. When a mote hears an older summary than its own, it broadcasts an update. Instead of flooding a network with packets, the algorithm controls the send rate. So, each mote hears a small trickle of packets, just enough to stay up to date. The network coordinator of the synchronized network is the sink, which is determined by two things: if the id of the mote is zero or the mote is connected to a PC and *UartDetect* has established a connection.

Figure 15 shows the graphical view of the components relation of *NetSync*. *NetSync* is wired to *SPC* (*Sensornet Protocol* Component) for sending and receiving

messages through this component. Usage of *SPC* makes it easy to implement and avoid any interference with the *MultiHop* component, while both messages can be transfered to lower layers with no more code development. Whenever *NetSync* has a message to send, it pushes the message to *SPC* by using *SPSend* interface. Also, whenever a message for *NetSync* is received at the mote, *SPC* delivers it to *NetSync* through *RecieveMsg* interface. *NetSync* uses other components for enabling timers, counters and connection recognition to the USB port. In order to be adapted to our application we have made some minor changes such as decreasing the interval between synchronization beacons. The reason for this change is that the clock drift makes the motes go out of sync. The main clock on the Tmote Sky runs on an internal DCO, which has a lot of frequency error (could be about 10%), unless the error is corrected through periodic recalibration with the crystal. We believe that the timers use the 32KHz crystal in TinyOS, which leads to a huge frequency error. This means that if we do not resynchronize the timer periodically, the clock drift could be unbounded.

3.3.7 Sensornet protocol

We used *Sensornet Protocol* (*SP*), which is a unifying link abstraction for running network protocols over a variety of link layer and physical layer technologies without changing network protocol implementation [63].

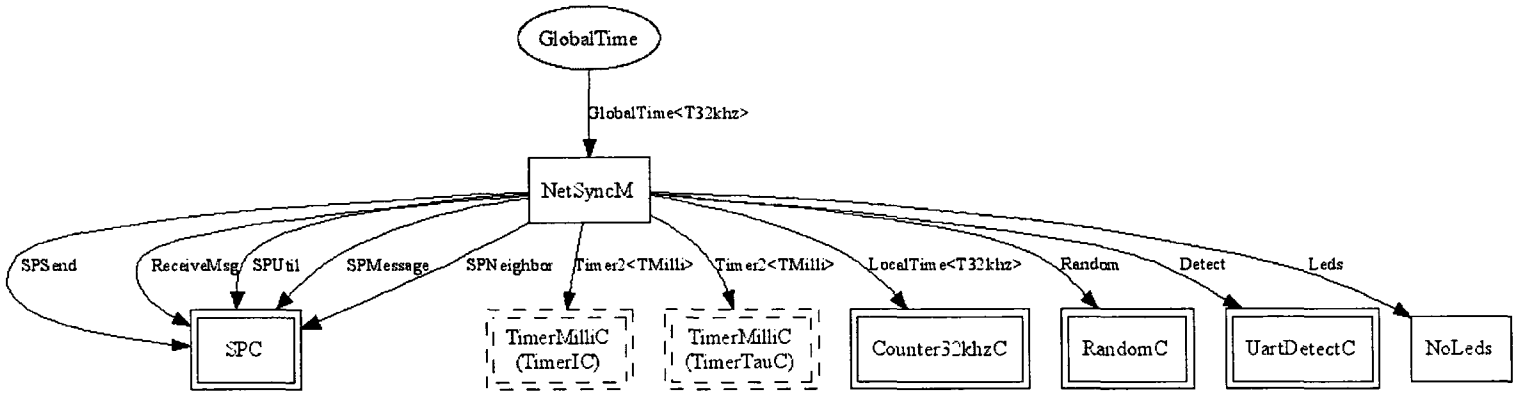


Figure 15: Graphical view of components relation of *NetSync* component

Figure 16 shows the graphical view of the components relation of *SPC* (*Sensornet Protocol* Component). In *SPC*, messages are transmitted using the *SPSend* interface and next messages are handled through the *SPSendNext* interface. In order to send a message on a particular message identifier type (such as type 5), we wire our network protocol to *SPSend[5]*. The *SP* message pool holds on to a message and its corresponding packets until it may be sent over the channel. Fields of each *SP* message (*sp_message_t*) can not be directly accessed. Instead, they can be set using the parameters of the *SPSend* interface.

Reception is on a per-packet-basis (not per-message-basis like *SPSend*). Packets are immediately dispatched to higher layer services based on message identifier type. It means if there is a message bigger than 125 Bytes (the maximum size of message that can be transmitted by the radio transceiver of Tmote Sky), the network protocol (higher level) is responsible to break it down and put it together in the other end. *SP Neighbor Table* is accessed through *SPNeighbor* interface. We wired the *MultiHop* component with the parameter unique (*SPNeighbor*) to *SP Neighbor Table*. Each service then has its own identity for controlling the insertions, removals, and changes to entries in the *SP Neighbor Table*.

The other main components of *SP* are as follows: *SPM* is the implementation of the primary state machine of SP for handling messages, both transmitted and received. SPM works with other components to send messages from the pool when appropriately notified by the *SP Neighbor Table* or the link protocol. *SPDataM*

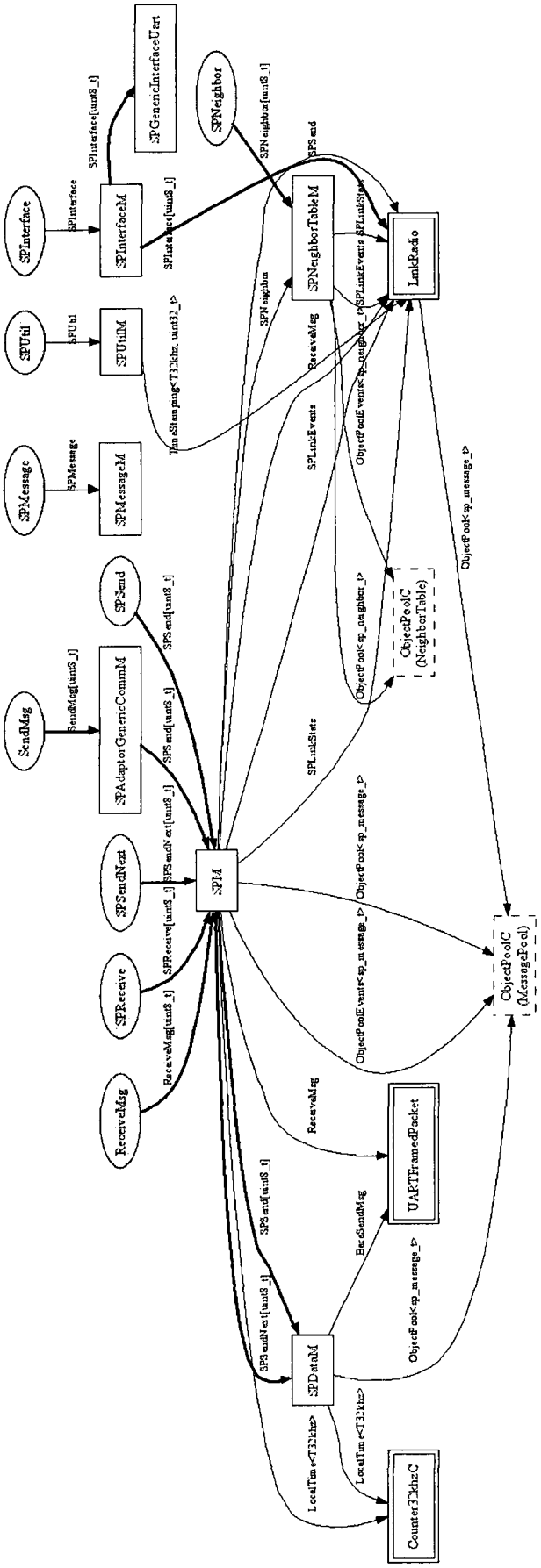


Figure 16: Graphical view of components relation of *Sensornet* component

sets the data fields of *SP* messages and TinyOS packets. It also maintains the SP Message Pool. *SPUtilM* is the implementation of the utility functions (link estimation and time stamping) for SP. *SPNeighborTableM* is the implementation of SP's Neighbor Table and associated management functions. *SPInterfaceM* is the SP Interface/Device query interface from Radio and USB port connection when the mote is working as the sink. *SPAdaptorGenericCommM* is an adapter that converts standard packets into SP messages, dispatches them to SP, and then decomposes the messages back into packets after transmission.

3.4 Gateway/server

As we explained in Section 3.2, our system has a gateway/server, which enables data messages from the sink to be forwarded to end user applications and archived in the database. The gateway/server is connected to the sink through a USB port and acts as a server for the end user applications. It should be connected to the end user and database through the Internet.

In this section, first we explain the design of the gateway/server. Then, we break down the main components and functionalities of it.

3.4.1 Design and features

Figure 17 shows the package diagram of the gateway/server. The three main packages of the gateway are *com.concordia.bm.motes*, *com.concordia.motesbridge*,

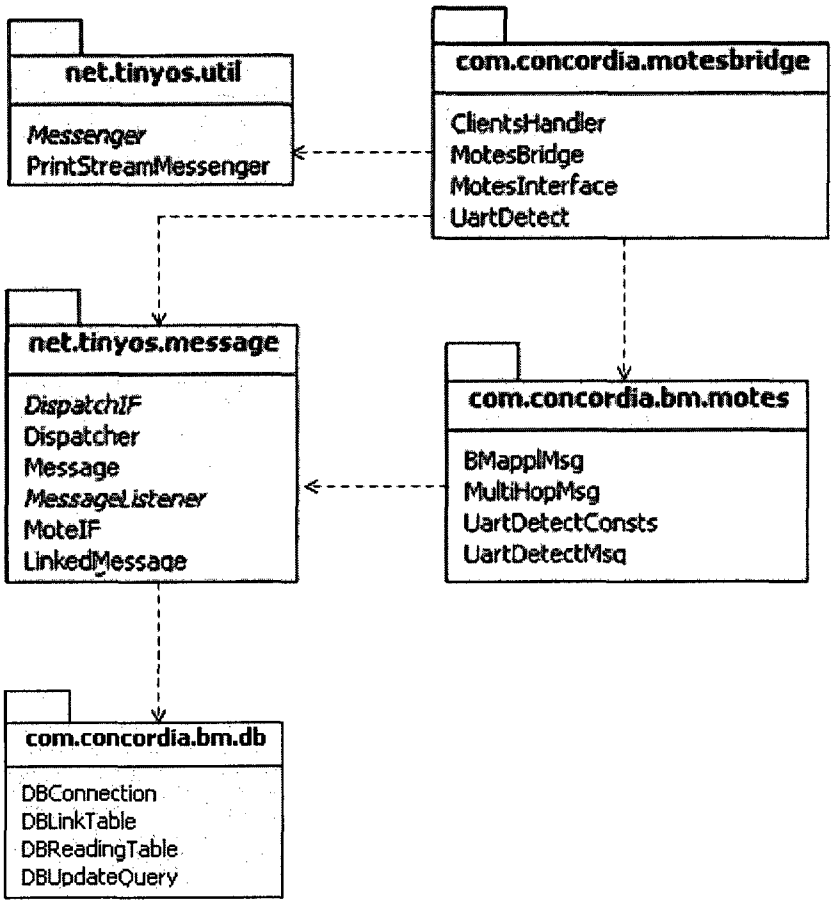


Figure 17: Package diagram of the gateway/server

and *com.concordia.bm.db*.

The *com.concordia.bm.motes* package includes classes for creating and accessing messages of motes. There are two kinds of messages: USB connection messages and data messages. USB connection messages are used to establish synchronized connection between the gateway/server and the sink. *UartDetectMsg* and *UartDetectConsts* are the classes for accessing and generating USB connection messages. Data messages are the collection of data from each mote in the network. They

consist of the header and data field. The header of data message is accessed by *MultiHopMsg* class. Data field of data message is accessible by *BMapplMsg* class.

The *com.concordia.motesbridge* package is responsible for connections to the sink and to the end user applications. In this package, *MotesBridge* is the main class, which initiates the gateway/server application. The initiation is done by using *UartDetect* class to find the connected mote to the PC and then establishing the connection. Then, the *MotesInterface* class makes a thread for listening to the sink and extracting data messages from *UartDetectMsg*. This class interprets the correctness of data messages. Concurrently, *MotesInterface* establishes a server for listening to the clients, which are the end user applications. Whenever a client (the end user application) connects to the server successfully, one thread will be created for the client and handed over to *ClientsHandler* class. This class is responsible for transmitting and receiving messages to and from each client.

The *com.concordia.bm.db* package is implemented to handle the database connection and includes all queries, which are used in the end user application for data archiving.

The gateway/server uses six auxiliary packages from TinyOS operating system for utility functions and one external library file, which is *comm.jar* for communicating through USB port. Complete class diagrams and package diagrams of the gateway/server are shown in Appendix B.

3.4.2 Sink connection

The gateway/server communicates with the sink through the USB connection synchronously. First, the gateway/server figures out which USB port is connected to the sink by scanning the ports. After finding the port, the gateway/server connects to the Tmote Sky with the baud rate of 57600. After the establishment of the connection, one thread gets set to receive the messages from the sink and another thread gets set to send messages to the sink. Then, received messages will be forwarded to all connected clients.

3.4.3 Internet connection

The gateway/server is running as a server and can accept connections from many clients. The connection is implemented based on reliable and connection-based TCP/IP protocol. Since TCP/IP is streaming the data, we cannot send messages in packets. Therefore, we used in-order-delivery feature of this protocol and extra header sent with each message to let the client distinguish separate messages. In the other words, we extract four pieces of information from each message and send them as the header of each message in the stream pipe. At the other end, client uses this information to distinguish separate messages. The four pieces of information are the message identifier, the message length, length of data field in the message and base offset of data field in the message. One thread is responsible for each client for sending and receiving the data.

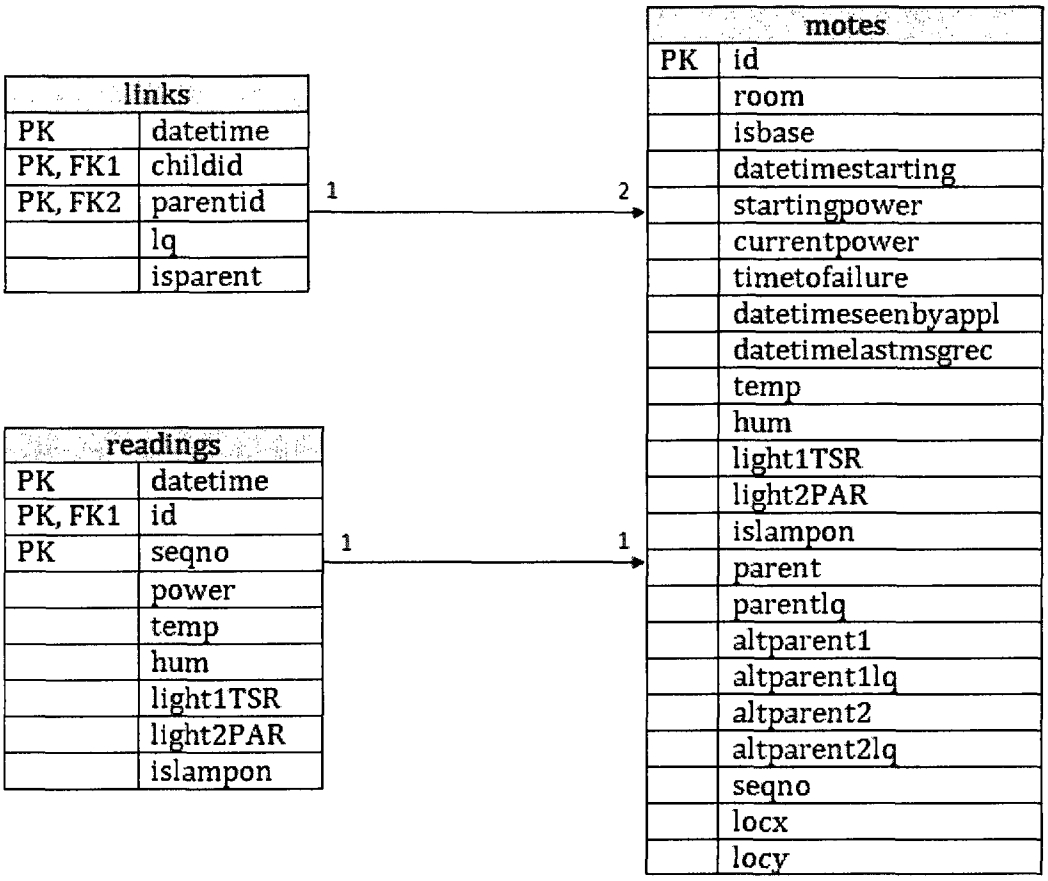


Figure 18: The database schema for bm database

3.4.4 Database

In the gateway/server, whenever a new message from a mote in the network is received and interpreted, the interpreted data has to be archived in the database for later retrieval and analysis. Therefore, we have defined a database in MySQL server 5.2. Figure 18 shows the schema of the designed database. As shown in the database schema, we defined three tables in this database. The fields and features of three tables are explained below:

***Motes* table:** This table has one row for each mote in the wireless sensor network. Therefore, the primary key of this table is id of the motes. This table keeps the information for the last status of each mote. The information archived in this table for each mote is explained in detail in Subsection 3.5.3. In this table, there are fields that are updated upon receipt of each message from the mote such as received messages, temperature, humidity, etc. However, there are other fields that are updated more rarely such as *Starting date and time*. The data in this table is retrieved by the end user application for different purposes in the application such as initiating the object for newly seen motes in the visualization process, filling the drop down list with list of motes in database in query and analysis tabs, and updating the last status of each mote in database based on newly received data message.

***Readings* table:** This table is used for archiving specific interpreted data from every messages received from the motes. The interpreted data archived in this table includes temperature, humidity, brightness by TSR sensor, brightness by PAR sensor, lamp status (room occupancy), and sequence number. The message interpretation is explained in Subsection 3.5.3. For each row in this table, besides the interpreted data from the message, the date and time of the message reception, and the id of the sender mote is archived in this table. For avoiding any redundant data, we defined combined primary key, which includes date and time, id and sequence number for this table. The foreign key of readings table is its id column,

which is pointing to the id column of the motes table.

In this table, one row is inserted whenever the new message is received from any mote in our wireless sensor network. The data in this table is retrieved by the end user application for analysis by the users, which are responsible for building management through *Building Managing Query & Analysis* tab, which is explained in subsection 3.5.7.

***Links* table:** All reported link information from the network gets archived in this table. Each link has the following information: id of child mote, id of parent mote, quality of the link, and whether the link is pointing to the current parent or alternative parent. Link information is reported by the messages received from the motes. Every message includes the link information to its current parent and at most two of its alternative parents. The interpretation of link information is explained in detail in Subsection 3.5.3. Therefore, the date and time of the message reception is archived in the table. The primary key of this table is the composition of date and time of message reception, id of parent mote and id of child mote. The foreign key is the id column of motes table.

In the *Links* table, at least one and at most three rows are inserted whenever a new message is received from any mote in our wireless sensor network. Data in this table is retrieved by end user application for analysis by the users, which are responsible for network administrating through *Network Administrating Query & Analysis* tab, which is explained in Subsection 3.5.8.

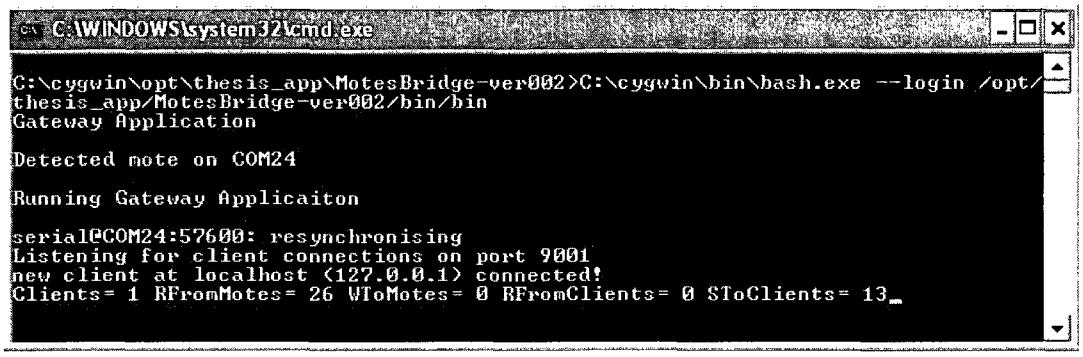


Figure 19: Gateway/server user interface

Finally, we have to mention that depending on the combination of the criteria and the category of analysis for archived data selected by the user, the end user application generates the required query and retrieves the requested data.

3.4.5 User interface

The gateway/server provides different information regarding the number of messages sent or received and connectivity status of the gateway/server to the clients and the sink. It also provides information about any malfunction in the application such as the receipt of corrupted messages from the sink or any inserting and updating problem with the database. Figure 19 shows the user interface for the gateway/server application.

3.5 End user application

The end user application is implemented in order to satisfy the user requirements mentioned in Subsection 1.2.1. The end user application is connected to the gateway to receive data messages and queue them for processing. Queued data messages are interpreted for wireless sensor network visualization and analysis. In the rest of this section, we explain the design and functionalities of the end user application.

3.5.1 Design

The end user application consists of eight main packages, six auxiliary packages and ten auxiliary external libraries. A partial package diagram of the main packages is shown in Figure 20. The auxiliary packages are from TinyOS operating system for utility functions to interpret data messages. The auxiliary external libraries can be categorized by their usage into database connection, topology visualization and data scaling. Appendix B includes complete class diagrams and package diagrams of the end user application. The packages that we implemented for our application are summarized below:

***com.concordia.bm*:** This package is the main package of the end user application. It initializes the end user application and connects all packages together. In addition, auxiliary classes for file handling, date and time calculation, mote data

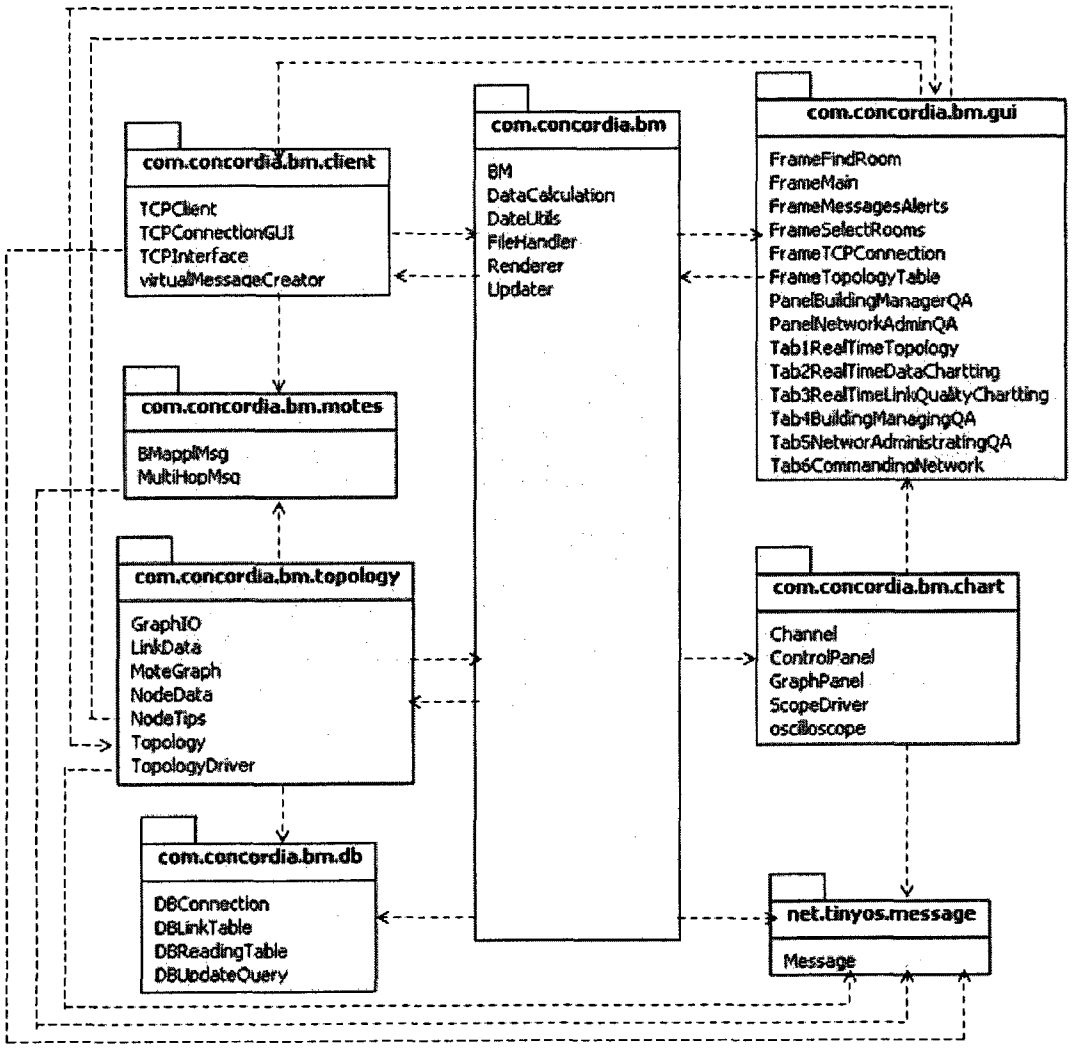


Figure 20: Package diagram of the end user application

calculation, and messages and alert rendering are implemented in this package.

***com.concordia.bm.client*:** This package is responsible for connection to the server. It also distinguishes separate messages from the stream connected to the TCP/IP layer and then queues them for processing.

***com.concordia.bm.topology*:** This package includes the classes responsible for data messages interpretation to enable the following tasks: visualizing real time network connectivity graph (topology), checking individual mote's information for correctness, updating tables and inserting new data in database by using *com.concordia.bm.db* package.

***com.concordia.bm.chart*:** This package contains the implementation of the scaling of real time data from the motes and retrieved data from database. Moreover, the panel including the charted data is generated in this package and handed over to the *com.concordia.bm.gui* package to be placed in main frames of the scaling tab.

***com.concordia.bm.gui*:** This package is used for forming the GUI for the end user application including main frames and tabs. This package is used for all of the user interfaces except the one for server connection, which is enabled by *com.concordia.bm.client* package and the one for topology visualization, which is implemented in *com.concordia.bm.topology.*

***com.concordia.bm.motes*:** This package includes classes for accessing and generating data messages structure to enable *com.concordia.bm.topology* to interpret the messages.

***com.concordia.bm.db*:** This package is implemented to handle the database connection and includes all queries, which are used in the end user application for data retrieval.

3.5.2 Server connection

Figure 21 shows the frame for server connection. In this frame, users enter the IP address of the server (the gateway) and appropriate port number for the gateway application to connect to the gateway. Users can connect to and disconnect from the gateway from this frame without any interruption in the application since the server connection is handled by one separate thread. All messages regarding connection confirmation, disconnection and any changes in the connection such as full buffer and server interruption is shown in the messages panel. The messages panel is described in Subsection 3.5.5.

After connection establishment with server, the data stream is received from the stream attached to the TCP/IP layer. Messages are recognized individually based on the header that we defined for each data message in Subsection 3.4.3. Then, data messages are reconstructed with classes in *com.concordia.bm.motes* and queued in *BM.newMessages* data structure, which is defined as a static vector. Therefore, for

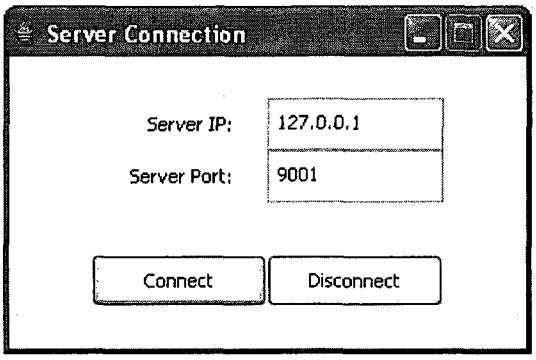


Figure 21: Server connection frame

different threads to have shared access to its contents and avoid thread interference and memory consistency errors, we have used the synchronization tool in Java.

3.5.3 Message interpretation

After the messages are queued in *BM.newMessage* vector, the Update class in *com.concordia.bm* reads the messages and forwards them to three different methods. Messages are forwarded to *readingsDriver.update(msg)* and *linkqualityDriver.update(msg)* for charting and *topologyDriver.update(msg)* for visualization. The message interpretation is done in *com.concordia.bm.topology* package and then, the data is available to other packages.

For each mote in the wireless sensor network, one thread is created in the end user application. Each thread is responsible for the visualization, charting, new message interpretation, and database update of the mote. For message interpretation, the classes in *com.concordia.bm.motes* are used to extract the raw data from different fields of the message. For each mote in the end user application, there is

different information, which is archived in the database, extracted from the messages or generated by the end user application. This information is provided for the users and the application for different purposes such as visualization, network analysis, etc. The provided information includes the following fields:

***Mote ID*:** It is the id of the mote which has sent the message. This value is extracted from the message to determine the source of the message. Then, the information of the determined source is updated.

***Room number*:** It is the description of the room or location in which the mote is placed. This field can be changed by the user in the application. Room information is saved in the database for letting the user have the information for later usages. This field is used for making the application more readable in the way that, the id of the mote will be accompanied by its corresponding room information.

***Is Base*:** This field is used for recognizing the sink from other mote. We have to have a way to distinguish the sink from the other motes in the end user application, since the sink in our wireless sensor network can have any id due to the fact that any mote can be sink if it satisfy one or both of the following conditions: id number equal to zero or established connection to the sink.

***Starting date and time*:** It is the date and time of the first deployment of this mote in the building. This field is set once in the application when the first message

of the mote is received by the application and it will never change until the power source of the mote is changed to the higher one. Every time the application is restarting, the value for this field is retrieved from the database. This information is used with three other pieces of information to calculate the linear estimation of *Time to failure* of the mote. Three other pieces of information are *Starting power*, *Current power* and date and time of the last received message.

***Starting power (V)*:** This field is set at the same time with *Starting date and time* information. Its value is the voltage of the mote's power source when it has been placed in the building for the first time. This information is used with other information for calculating the linear estimation of *Time to failure* of the mote. The *Starting power* is retrieved from database whenever the end user application is started. If the mote's power increases at least 0.2 voltage due to renewing the batteries of the mote, the *Starting power* value will be changed to the current voltage. At the same time, *Starting date and time* of the mote is updated to current date and time.

***Current power (V)*:** This field is the current power of the mote in voltage. Based on Subsection 3.3.1, *Starting power* and *Current power* are calculated in the application.

***Time to failure (days)*:** In our application, the *Time to failure* for each mote is the estimated number of days for which the mote is operational. Tmote Sky

motes are operational with a supply voltage of at least 2.0V [36]. In the end user application, the current supply voltage of each mote is received by its message. Therefore, we can calculate the estimated *Time to failure* of the motes based on their current power and the voltage performance of the motes' power supply, which is two AA Alkaline batteries [20]. The *Time to failure* of the motes can not be calculated without considering the batteries brand since the chemistry and internal resistance of individual batteries from different brands are not the same. In addition, we can not calculate the exact *Time to failure* of each mote due to the dependency of the voltage performance of the supply batteries to the voltage and current drainage, and temperature [20].

Each mote's power consumption with radio on is 20mA and with radio off is 10μA. Therefore, the mote with 5% duty cycle consumes about 1009.5μA (almost equal to 1mA). Based on the data sheet of Eveready AA Alkaline battery, with continuous current drainage of 1mA at temperature of 21°C, the battery voltage reaches 1V in 2600 hours [20]. Thus, the supply power of the motes, which is 2 such batteries is reaching its minimum useful voltage level, which is 2V in 2600 hours. We can define the equation for calculating the remaining lifetime of the mote based on its current batteries' voltage by using the following equation:

$$Y - y_1 = \frac{(y_2 - y_1)}{(x_2 - x_1)}(X - x_1)$$

In above equation the Y is the cut off voltage of two batteries and X is time passed

in hours to reach this voltage. We have two data points of the equation, which are (x_1,y_1)=(0,3) and (x_2,y_2)=(2600,2). Therefore, by using the two data points, the equation will become as follows:

$$Y - 3 = \frac{(2-3)}{(2600-0)}(X - 0)$$

$$X = (3 - Y)2600$$

Then, we can calculate the remaining lifetime by subtracting the result of above equation from the calculated lifetime of the motes from Subsection 3.3.6. In Subsection 3.3.6, we calculated the lifetime of each mote for three different duty cycles (100%, 5% and 1%) based on the current consumption by the motes and the supplied current per hour by the batteries. The required duty cycle for our network is 5% by which the calculated lifetime of each mote is 107 days (2568 hours). Therefore, the *Time to failure* of the motes in hours is calculated as follows:

$$TimetoFailure(hrs) = 2568 - (3 - Y)2600$$

$$= 2600Y - 5232$$

$$TimetoFailure(days) = \frac{2600Y - 5232}{24}$$

Seen by appl on **(Date and time at which the message is seen by the application):** The value of this field shows the time and date in which the end

user application has been (re)started and received the mote's message. This field is set at each starting time of the end user application and will never change until next restart. This piece of information is used to determine how long the real time number of received messages and lost messages is calculated for.

***Last msg received on* (Date and time of last received message):** This field is updated whenever a message is received from the mote (every 30 seconds). This field is used for calculating *Time to failure* of the mote and checking the date and time of last status of the mote.

Temperature (°C): This information is extracted from the mote's message every time a new message is arrived. The unit for this field is °C. Based on Equation 2 in Subsection 3.3.1, we implemented the real time calculation of *Temperature* field.

Humidity (%): This field is the last reported true humidity of the room in which the mote is placed. The unit of this field is percentage. Based on Equations 3 and 4 in Subsection 3.3.1, the real time calculation of true humidity is implemented in our application.

Brighness (Lux): In each message from the mote, there are two fields containing data for brightness calculation. These two fields are *light1TSR* and *light2PAR*. These fields have the value of the room brightness in which the mote is placed.

Although we archive the calculated brightness from the value of both fields in the database, the value from *TSR* sensor is just used to show the measurement of brightness in the graphical user interface due to its higher accuracy and range of light spectrum coverage than *PAR* sensor. Based on Equations 5, 6 and 7 in Subsection 3.3.1, we implemented the real time calculation of brightness from *TSR* and *PAR* sensors readings.

***Lamp status (room occupancy)*:** This field determines the status of the lamps (on/off) in the room. The status of the lamp is used for two purposes, energy usage and room occupancy monitoring. For determining room occupancy, we used the status of the lamp in such a way that when the lamps are on the room is full and when the lamps are off the room is empty. The calculation of the lamp status is done by the mote itself and just the result is sent to the end user application. The calculation of lamp status is explained in Subsection 3.3.4.

***Parent id and link quality*:** Parent information of the mote is provided by the message. It determines which mote in the network is considered by the mote as its next one-hop forwarding neighbor. Parent link quality is the quality of the link from the mote to its parent. These information is also used for visualization purposes.

***Alternative parents ids and link qualities*:** In each message, in addition to the parent id and link quality, information about maximum two of the mote's

other neighbors is also sent to the end user application. The information about each neighbor includes their ids and link quality. The values of these fields in the end user application are updated with reception of every message. They are used to draw the connectivity graph of the network and analyze the connectivity of each mote in the network.

***Sequence number*:** The sequence number and id of the mote together are used to calculate the received and lost messages, and drop redundant data messages delivered to the end user application. Sequence number is extracted from the *BMappl* message encapsulated in data message.

***Number of received and lost messages*:** These fields are calculated for every mote in real time in the event of new message reception. Based on every message's sequence number, the end user application can calculate the number of received and lost messages since the start time of the end user application.

***X and Y coordinations*:** These two fields are the coordinates of the mote location in the visualization panel. These fields are used for making the visualization panel more user friendly, in such a way that if the user drags and drops the motes in this panel, rotate the whole network or change the angels of it, the values of X and Y coordinations of each mote is updated accordingly and archived in the database. Then, in case of restarting the program, the motes will be shown on the panel in the last place they have been left before the application was closed.

All above mentioned information for each mote is provided for the end user. Figure 22 shows the graphical user interface for showing the information of the selected mote. The user can see the information of any mote by selecting the mote from the drop down menu or by clicking on it on the visualization panel. In addition, the end user can modify the room information of each mote by entering the new information in the text box in the panel and then, clicking on *Update Selected Mote* button. The new *Room number* will be updated for the mote in the database and visualization panel.

The user not only can see the information of an individual mote (room), he/she can also see the information of all motes (rooms) together by clicking on the button named *All Motes Overview*, which causes a frame titled *All Motes Overview* to be opened as shown in Figure 23. This frame shows the information of all active motes (rooms) in a table format based on real time data provided by last received message from each mote in the wireless sensor network. The motes can be sorted by their id or each individual field by clicking on the header of each column. In addition, the user can replace the columns position in the table for better readability. Moreover, the columns width can also be widened or shortened. Furthermore, this frame provides the following functionalities over the table:

- ***Print***: The table can be printed directly from the application.
- ***Save***: The user can save the table in a format readable by Microsoft Excel application for further analysis, adjustment or later access.

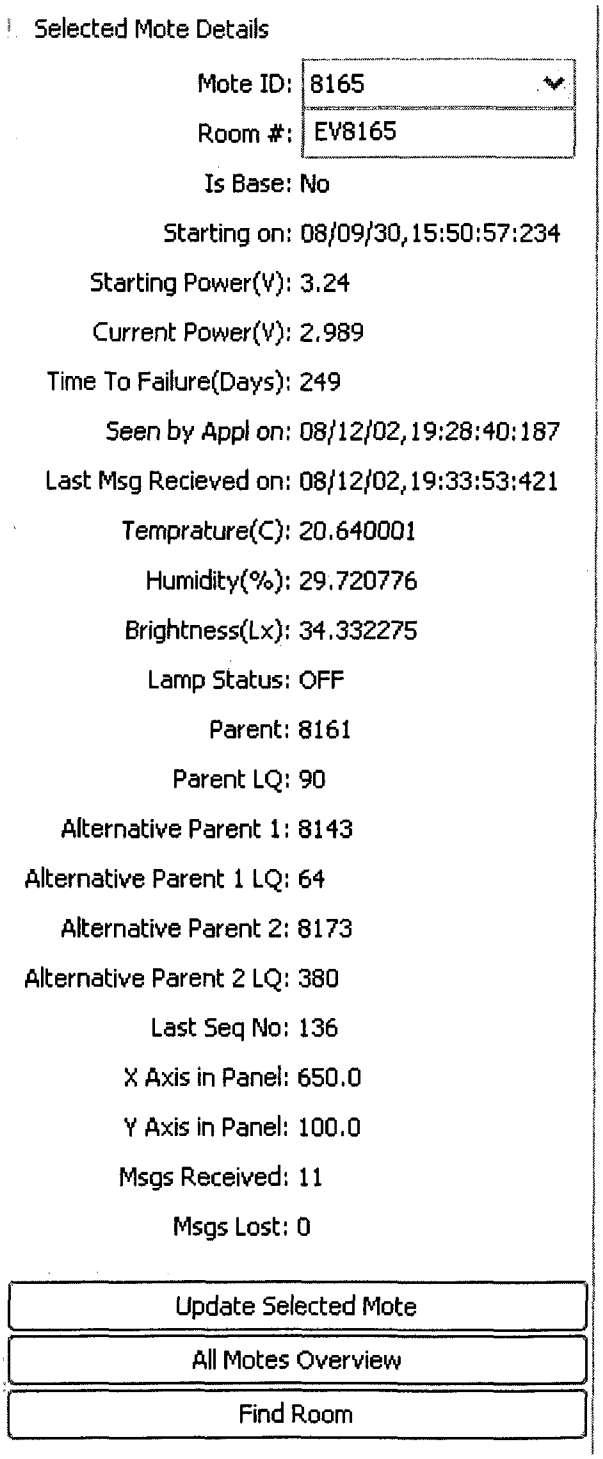


Figure 22: The graphical user interface for showing the information of selected mote

- ***Refresh:*** The user can refresh the table by using the *Refresh* button to have the most recent information for the motes.

Furthermore, the user can search for the rooms (motes) based on their current temperature, humidity, brightness, lamp status (room occupancy), and power of placed mote in that room. To do the search, the user has to define the range of values for one or more of the mentioned fields. The *Find Room* frame, which is shown in Figure 24 enables this functionality. This frame can be opened by clicking on the *Find Room* button. In this frame, the user can define the field(s) with specific range of values to be considered for search by checking appropriate box(es). In this frame, there are also extra utility functions such as reseting the defined criteria for search, saving the search result or cleaning the result panel.

3.5.4 Real time topology visualization

Figure 25 shows the *Real Time Topology* tab in the main window of the application. The *Real Time Topology* tab consists of three panels. The middle panel shows the network connectivity graph of the wireless sensor network. The information of the selected mote is shown in the right panel (explained in Subsection 3.5.3). This panel also has buttons for updating the *Room number* of the selected mote, searching the rooms based on current room condition and mote's power, and overview of all of the active motes. The bottom panel contains the controls for visualization as well as the *Save Topology* button. We explain the visualization

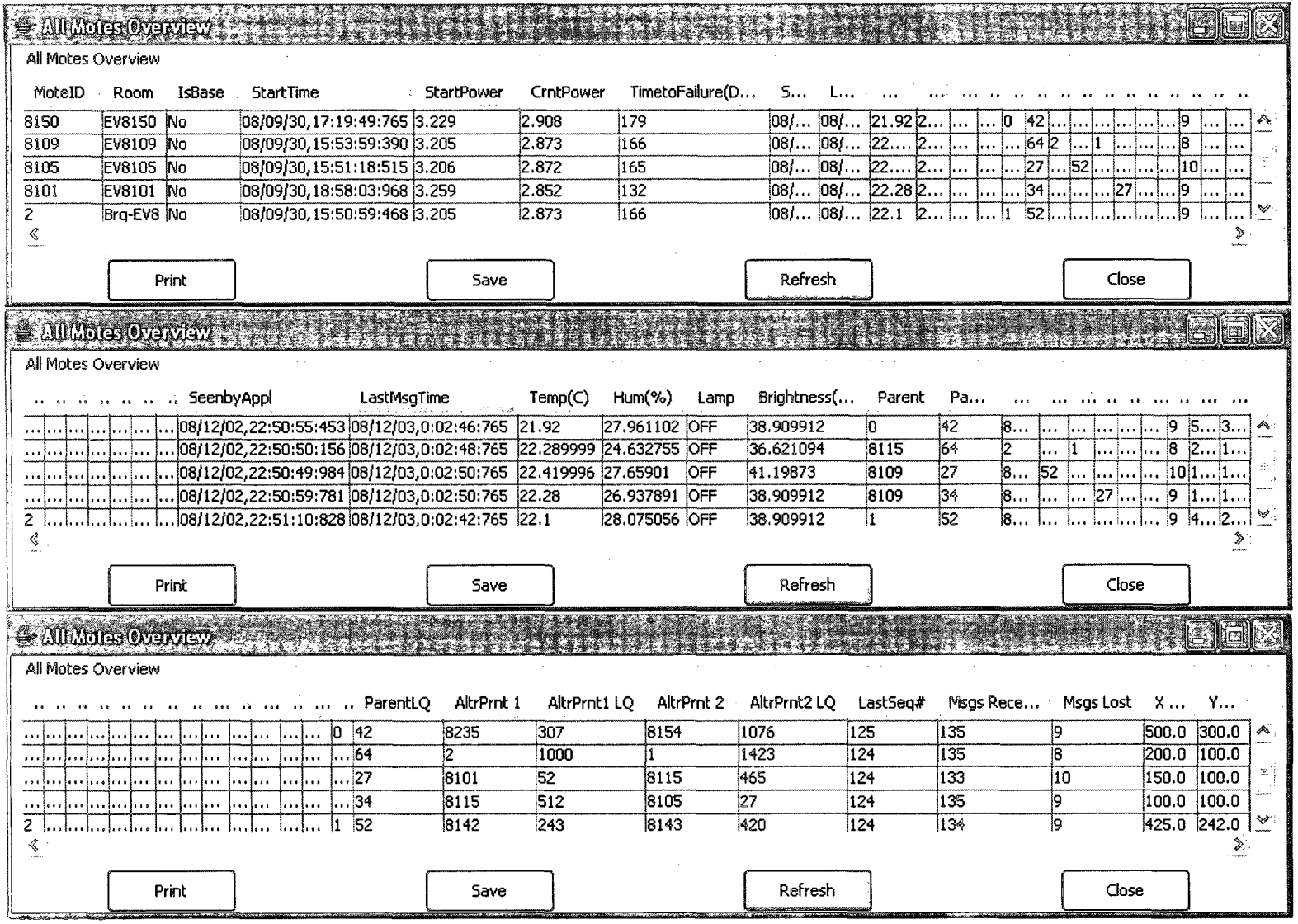


Figure 23: The graphical user interface for showing the information of all motes

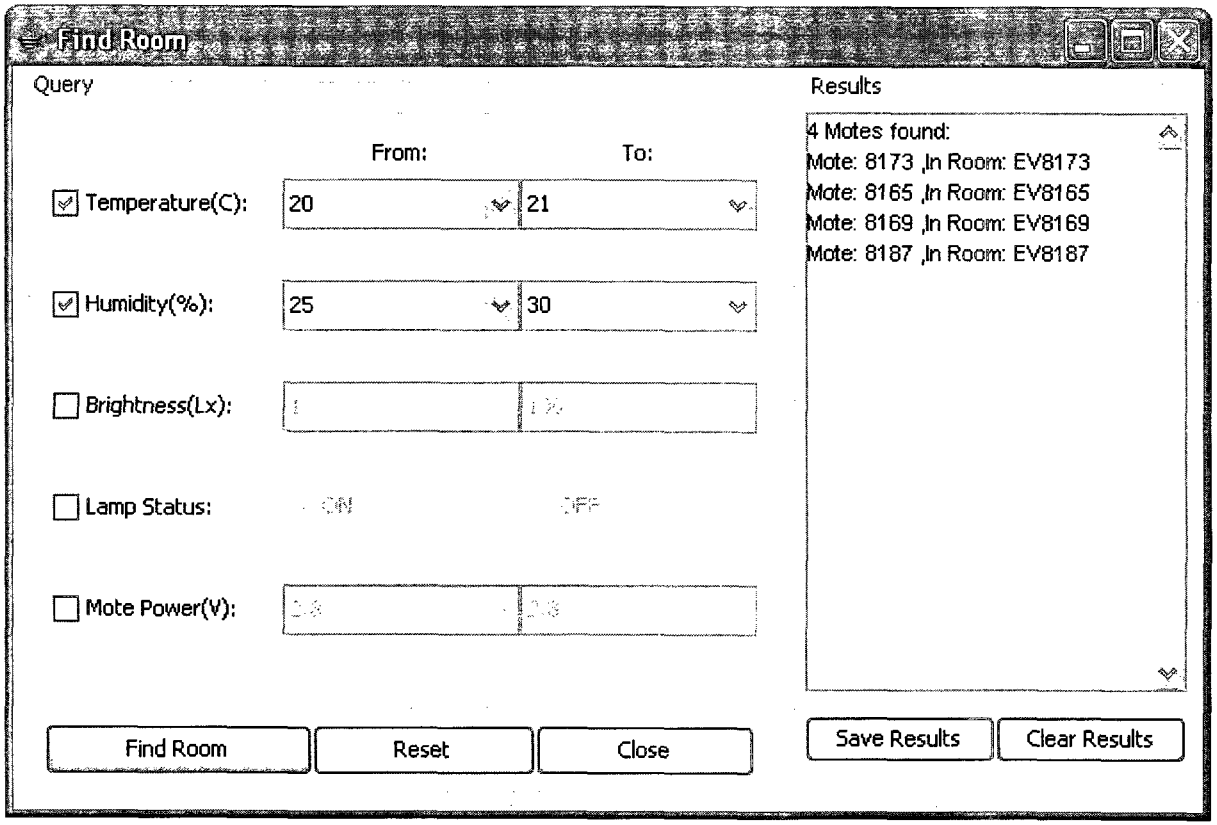


Figure 24: The graphical user interface for finding the rooms with defined criteria

and controlling panel in this subsection.

In the connectivity graph of the network, each vertex represents one mote in the wireless sensor network. All motes in the visualization panel are shown in red, except the sink, which is shown in blue. Each directed edge represents the link from the mote to its one-hop neighbor motes (parent and alternative parents). The link from the mote to its parent is shown in black and the links from the mote to its alternate parents are shown in gray. Each mote has exactly one parent except the sink which does not have any parent. In addition, each mote has at most two alternative parents. All black links together show the collection tree. The collection tree is rooted in the sink. Moreover, all links together show the connectivity graph of the network. The weight of each directed edge shows the link quality from the child to the child's parent. The lower this value is, the better the link quality would be.

In the visualization panel, the background picture is the map of a specific floor of the building. Over the floor map, the vertices are placed over the rooms in which the motes are placed. The end user has many functionalities in the visualization panel by interacting directly with the panel and by using the control panel, which is shown in Figure 26. These functionalities are as follows:

- **Changing the update frequency for topology:** The user can change the frequency for updating the network topology visualization by using *GUI Update Frequency* sliding bar. The network topology visualization is updated

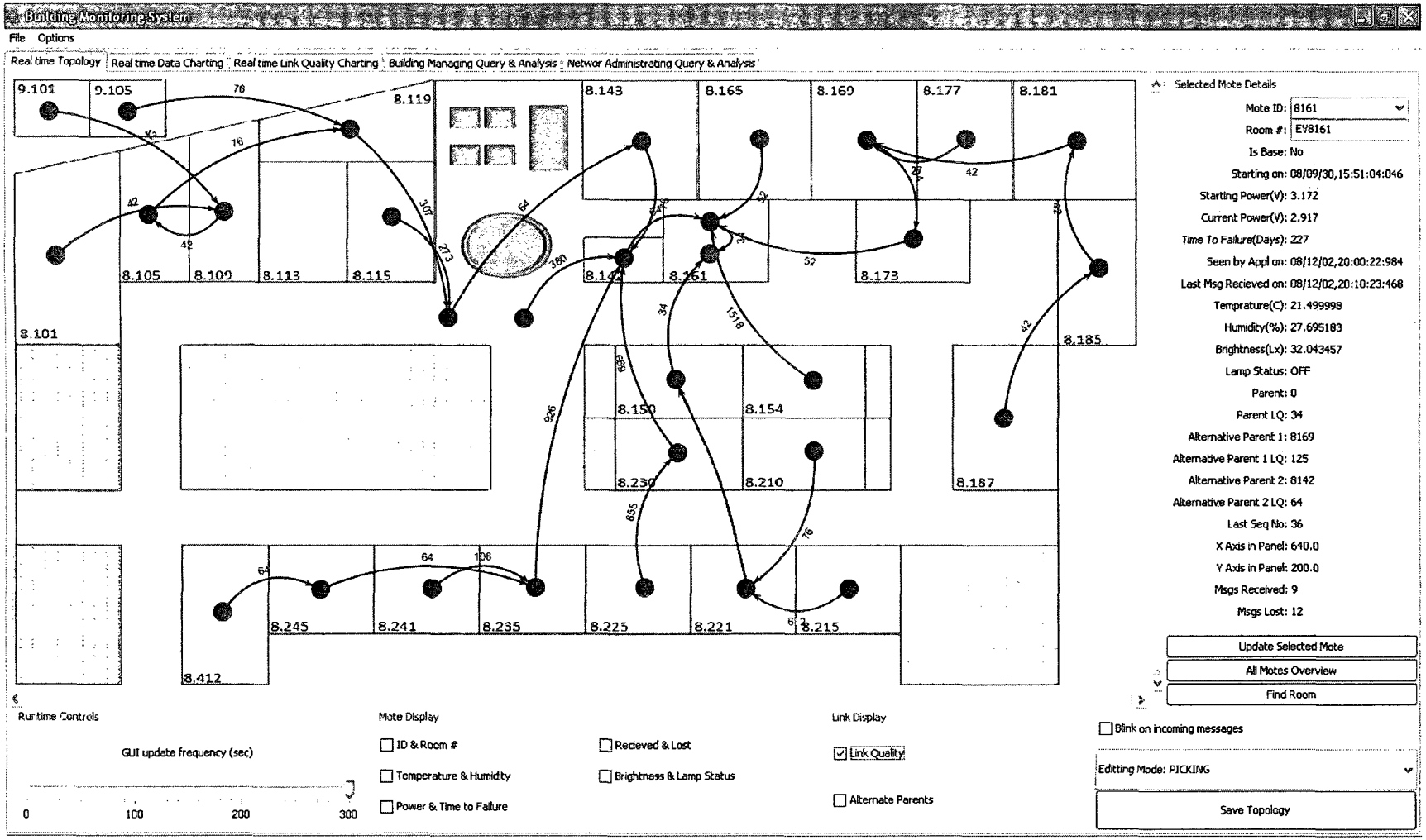


Figure 25: The graphical user interface for real time visualization of the network topology

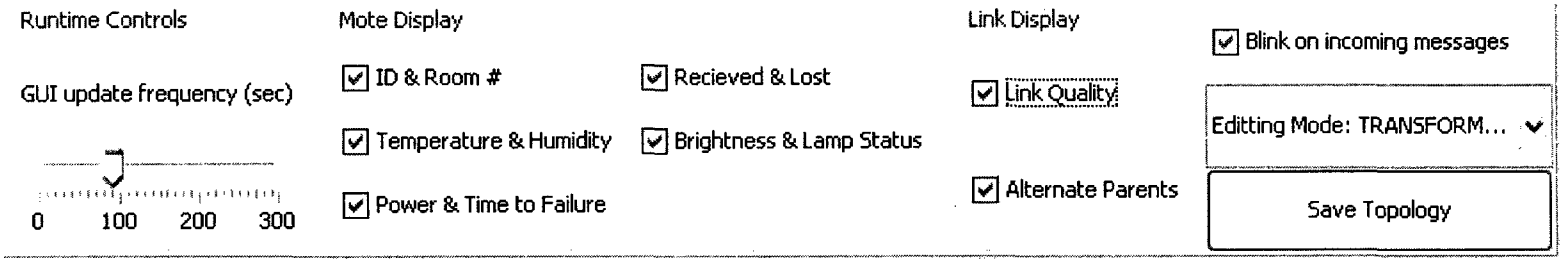


Figure 26: The graphical user interface for controlling the visualization panel

based on every message sent from the motes. This update task includes adding new links for the alternative parents or the current parents and removing the old ones. This update task also includes changing the information, which is selected to be shown in the panel for each mote. Message from the motes is generated every 30 seconds. Thus, the topology information changes very often. The user has the ability to increase the update intervals to see the network without frequent dynamic changes to be able to study and analyze a static view of the system.

- **Selecting the desired information for the motes to be displayed:** The user can select from none to all of the following information to be shown for each mote in the visualization panel: *ID & Room #*, *Temperature & Humidity*, *Brightness & Lamp Status*, *Power & Time to failure*, and *Received & Lost Messages.*

- **Selecting the desired information for the motes connectivity to be displayed:** The user can select whether the link from the motes to their alternative parents is to be shown or not with or without the quality of each link.

- **Blinking on incoming messages:** The color of the sink in our application is solid blue and the color of all other motes is solid red. The user has the option to see the motes blinking upon receiving a new message.

- **Changing the editing mode for rearranging the motes in visualization panel:** The user can rearrange the placement of the motes in the visualization panel. For rearrangement, there are three modes, which are *Picking*, *Transforming* and *Fix* . *Picking* mode enables the user to select each mote for displaying its information in *Selected Motes Detail* panel, to select one or more motes together to move in the panel, and to zoom in and zoom out in the panel. *Transforming* mode enables the user to rearrange the whole topology by making circular, rotational and dragging movement. Finally, *Fix* mode locks the graph.

- **Saving topology:** The user can also save the topology visualization of the network in the JPG format by using *Save Topology* button. By clicking this button, a browser window will be opened to enter the name and location of the file to be saved.

Figure 27 shows the information that can be shown at the same time in the visualization panel.

3.5.5 Messages and alerts central panel

Figure 28 shows the central panel for displaying messages and alerts generated by the end user application. In our application, messages and alerts are the information provided for the end user to be informed or take the proper action accordingly. Messages provide information about the results of the tasks which

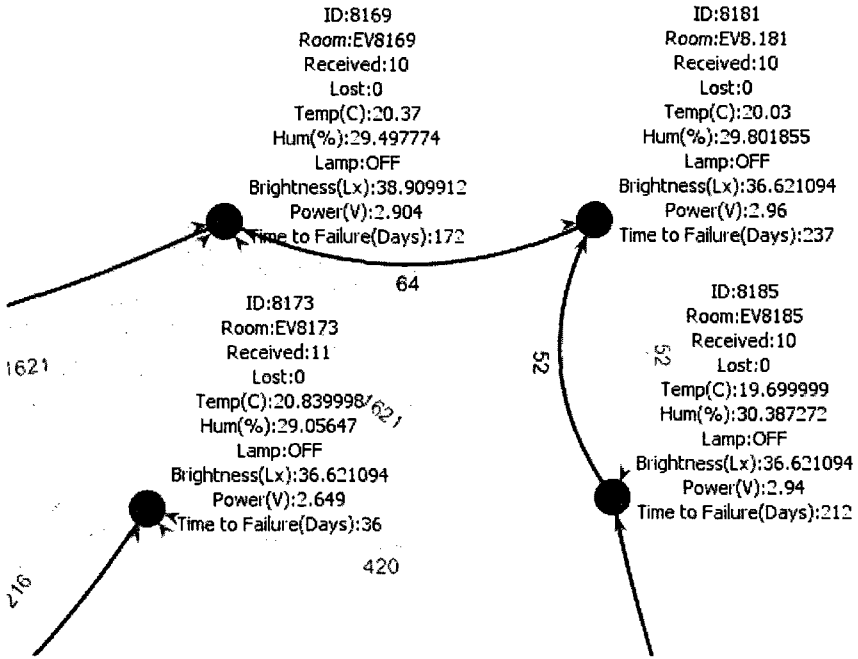


Figure 27: The Information that can be shown in the visualization panel for the motes and their connectivity

have been performed in the end user application. These tasks can be related to the communications to the gateway/server and message arrival from the wireless sensor network. The tasks are performed by either the end user or the application itself. Examples of the messages are successful connection to the gateway, the gateway interruption, new detected mote in the network, mote with delayed messages, creation of new channel in real time data charting, etc.

Alerts in the end user application are about the condition of motes in the network or condition of rooms sensed by the sensors. Alerts are generated in cases of sensing very high or low temperature or humidity, sensing a very high luxe of brightness, or reporting a mote very low in energy sources. For the safety of the building tenants, proper actions have to be performed to urgently resolve the alerts generated as a result of unusual room climate conditions. As well, the alerts generated as a result of reported dying motes have to be dealt with for keeping the connectivity of the wireless sensor network.

We implemented the central messages and alerts panel to enable the user to work with different parts of the application such as querying and analyzing archived data, since he/she can have the up-to-date status of the real time threads of the end user application dealing with the received data messages from the wireless sensor network concurrently. The messages and alerts panel each can be separately cleaned and also saved in the text file for later reference.

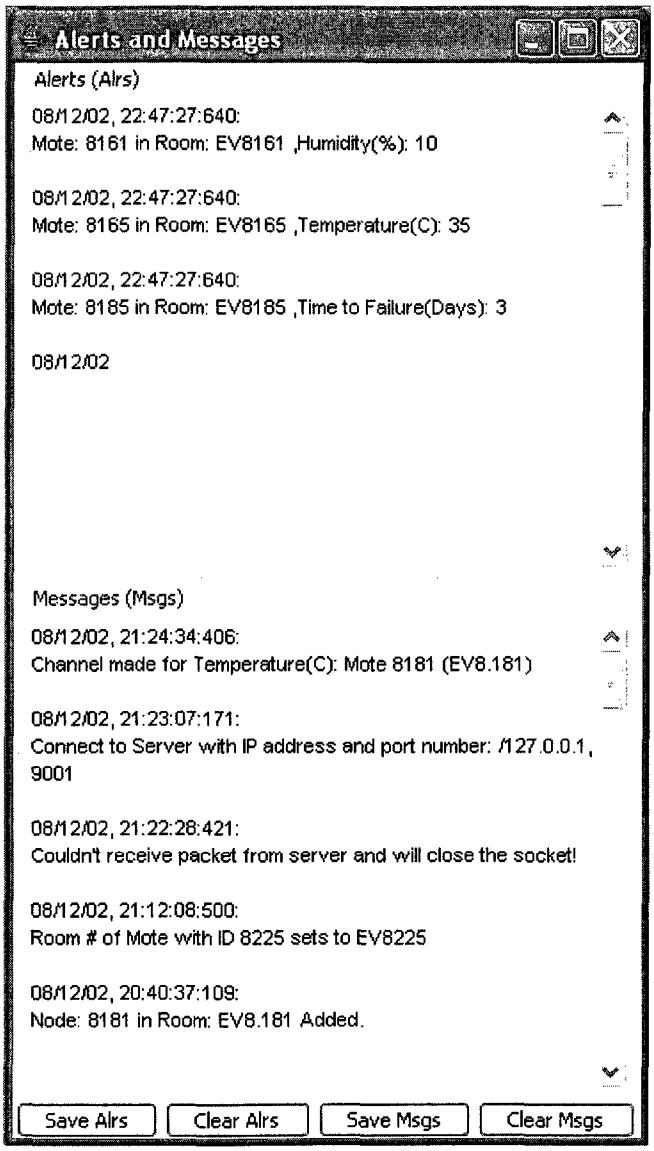


Figure 28: The graphical user interface for displaying messages and alerts of the system

3.5.6 Real time data and link quality charting

There are two tabs in the end user application for charting the real time sensed data and real time link quality of the links. These two tabs also provide the users with functionalities to analyze the received data from the motes in real time. Figure 29 shows the tab for charting real time sensed data and Figure 30 shows the tab for real time link quality charting.

In both tabs, the graphs for different motes are generated in different colors. In addition, the X axis of both sensed data and link quality charting is the time in which the charted data is received. The unit of this axis is second and it gets reset each time the new sets of motes is selected for charting their sensed data or link quality of their links to their neighbors. The unit of Y axis depends on the type of data being charted. In sensed data charting, the unit for Y axis is degree Celsius for temperature, percentage for humidity, Luxe for brightness and Milli-volts for the power. In link quality charting, the Y axis is not in specific SI unit.

In the tab for charting real time sensed data, the user can select the desired motes and data type by clicking on *Edit Legend* button. The *Edit Legend* frame for this tab is shown in Figure 31. In this frame, up to five active motes can be selected from drop down lists for charting the selected data type.

For charting the real time quality of the motes' links, the user can select the desired motes by clicking on *Edit Legend* button. The *Edit Legend* frame for this tab is shown in Figure 32. In this frame, up to five active motes can be selected

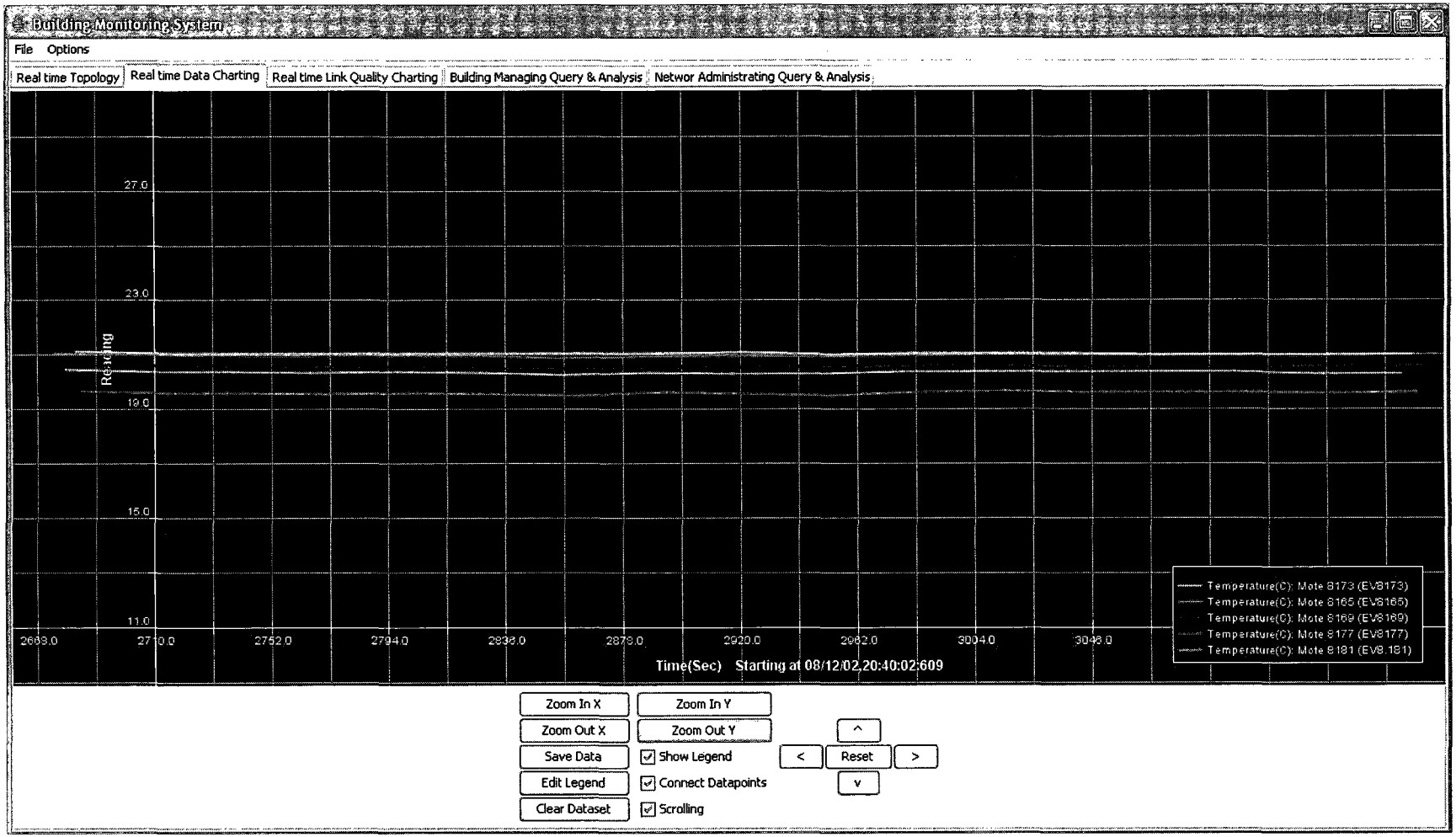


Figure 29: The graphical user interface for charting the real time sensed data

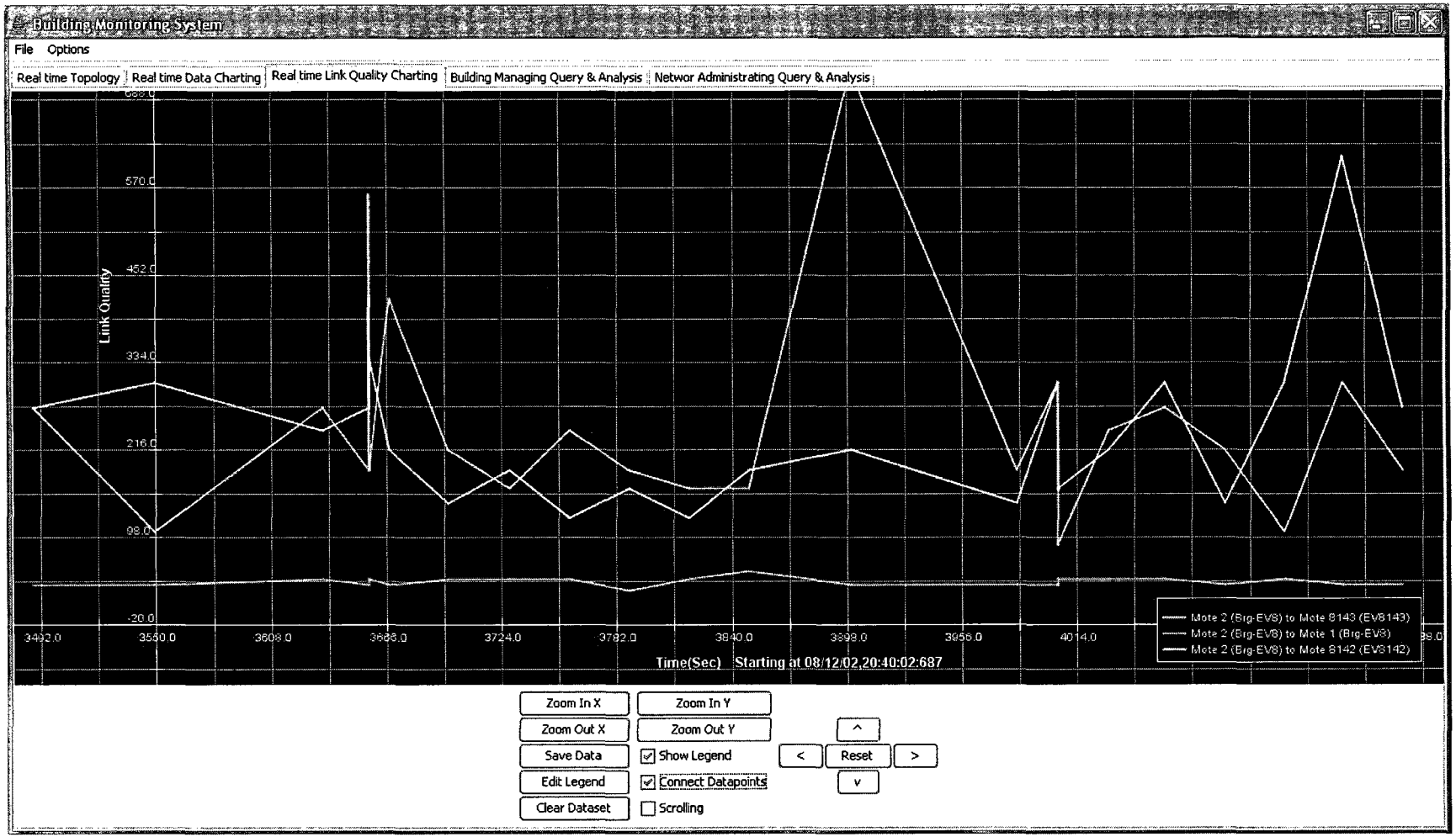


Figure 30: The graphical user interface for charting the link quality of the links

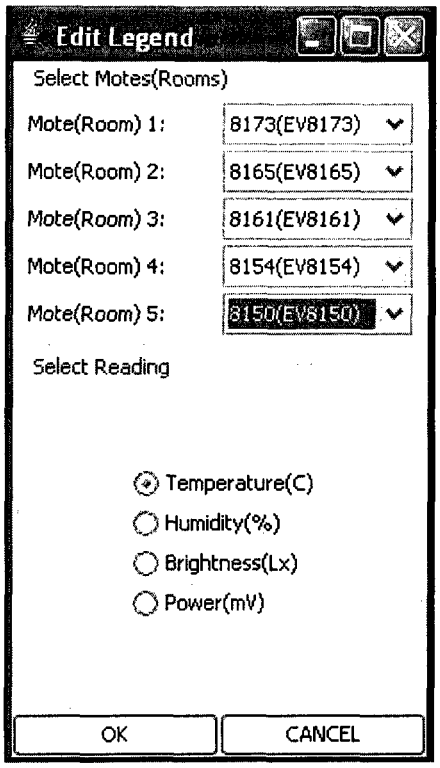


Figure 31: The graphical user interface for editing legend of real time data charting

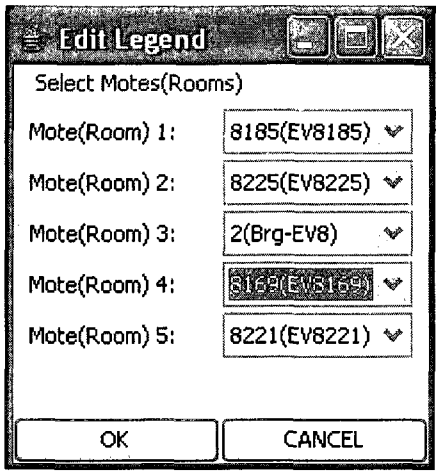


Figure 32: The graphical user interface for editing legend of real time link quality charting

from drop down lists for charting the quality of their links to their neighbors. For each selected mote for charting, there is at least one curve for charting the quality of the link to its current parent. However, in this tab, the quality of each mote's link to its alternative parents is also charted. Therefore, depending on the number of parents plus alternative parents which are selected by the mote during the charting time, there are separate graphs created for the link from the mote to each of the motes selected as parent or alternative parent. For instance, if the mote with id 1 is selecting 6 different parents and alternative parents combined during the time of charting, there will be 6 different curves created for the links from mote 1 to each of those 6 motes.

In both charting tabs for sensed data and link quality, the end user can do specific actions on the charts as follows:

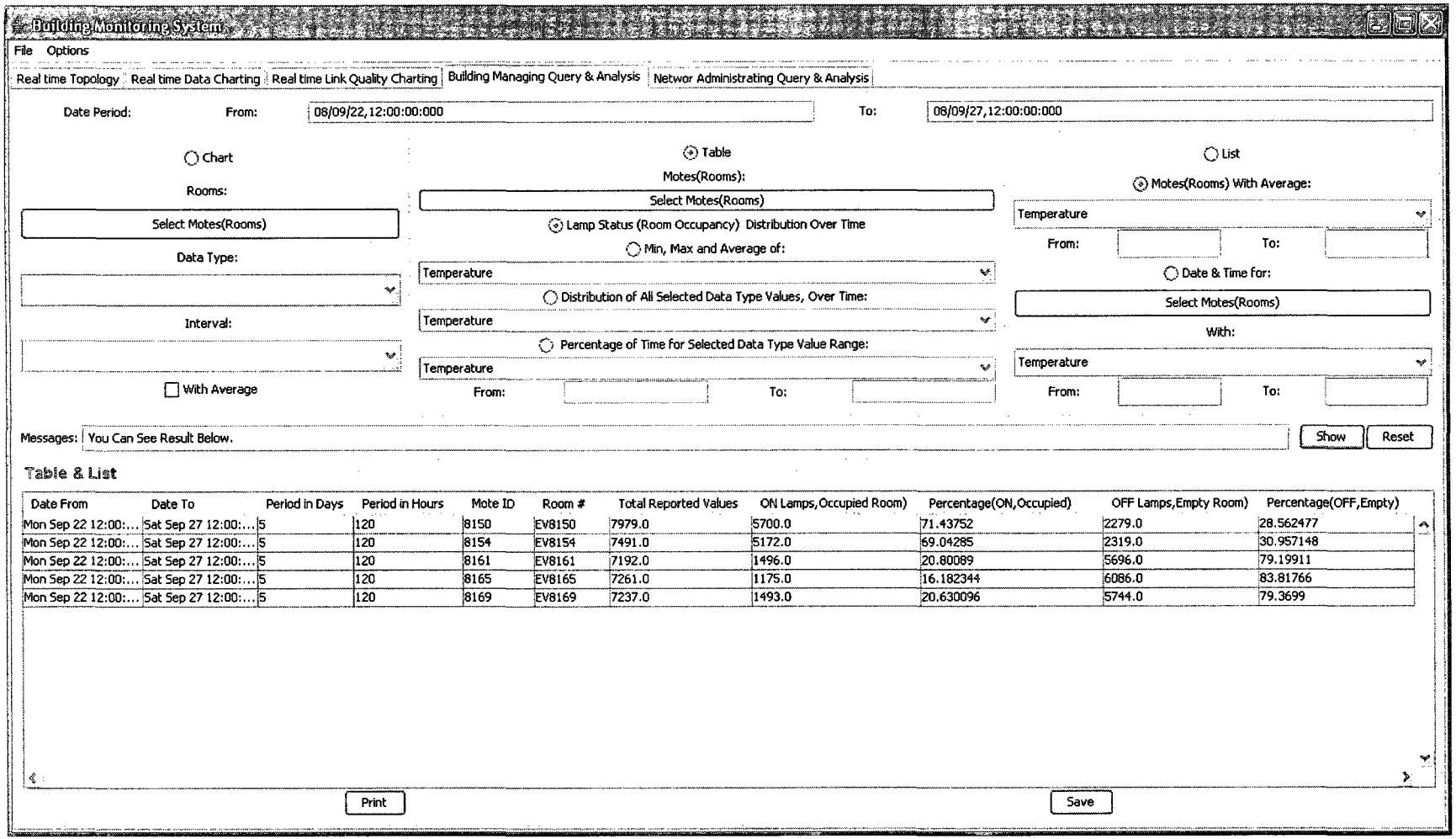
- Navigate the graph

- Zoom in and out
- Show legend
- Get exact coordinates of a data point
- Connect data points
- Auto scrolling
- Save data
- Clear dataset

3.5.7 Data query and analysis for building managing

All received messages from the motes are interpreted and archived in the database for later retrieval and analysis by the gateway/server. The database schema and details are explained in Subsection 3.4.4. Our system has two categories of users which are responsible for managing the building and administrating the wireless sensor network. For each category of the users, we implemented separate tabs in the end user application. The tab which is used mostly by the users managing the building is called *Building Managing Query & Analysis* shown in Figure 33. The other tab which is used by other category of the users is explained in Subsection 3.5.8.

The *Building Managing Query & Analysis* tab is used for retrieving and analyzing sensor readings including temperature, humidity, brightness from TSR,



Date From	Date To	Period in Days	Period in Hours	Mote ID	Room #	Total Reported Values	ON Lamps,Occupied Room)	Percentage(ON,Occupied)	OFF Lamps,Empty Room)	Percentage(OFF,Empty)
Mon Sep 22 12:00:...	Sat Sep 27 12:00:...	5	120	8150	EV8150	7979.0	5700.0	71.43752	2279.0	28.562477
Mon Sep 22 12:00:...	Sat Sep 27 12:00:...	5	120	8154	EV8154	7491.0	5172.0	69.04285	2319.0	30.957148
Mon Sep 22 12:00:...	Sat Sep 27 12:00:...	5	120	8161	EV8161	7192.0	1496.0	20.80089	5696.0	79.19911
Mon Sep 22 12:00:...	Sat Sep 27 12:00:...	5	120	8165	EV8165	7261.0	1175.0	16.182344	6086.0	83.81766
Mon Sep 22 12:00:...	Sat Sep 27 12:00:...	5	120	8169	EV8169	7237.0	1493.0	20.630096	5744.0	79.3699

Figure 33: The graphical user interface for querying database and analyzing retrieved data by the users responsible for building managing

brightness from PAR, and calculated data which is lamp status (room occupancy). In this tab, first the user has to define the period of time in which he/she wants to analyze the received data from the motes about the rooms condition. Then, the user can select one of the following categories to observe the analyzed data:

Chart: The chart category is used for charting the selected type of data for selected motes (rooms) in the defined period of time with defined intervals. After defining the criteria for charting data by the user, the chart will be shown in a separate frame by clicking on the *Show* button. Except for *Editing Legend*, the charting frame has the same look, features and functionalities of the tab for real time sensed data charting which is explained in Subsection 3.5.6. For charting different data type for different motes, the user has to do it through the *Building Managing Query & Analysis* tab.

Table: The table category is used for showing the analysis of the retrieved data from the database in tabular format. As we can see from the Figure 33, the user can have different tabular analysis for selected motes (rooms) and data types. After selecting the motes and data type, and defining the criteria, the tabular analysis of the data is shown in the bottom panel of the tab. The shown table can be printed or saved in a file. The saved file is executable by Microsoft Excel application for further manipulation of the data such as drawing pie diagrams.

List: The list category is used for listing two sets of data. The first set is about listing the rooms (motes) with defined range for average of selected data type sensed during the defined period of time. The second set is the dates and times in which the selected mote (room) sensed the selected data type in the defined range. The list are shown in the bottom panel of this tab. The lists can also be printed or saved in a file.

In *Building Managing Query & Analysis* tab, whenever the user wants to select motes for analysis, he/she has to click on *Select Motes (Rooms)* button in the appropriate category. After clicking on the button, the new frame titled *Select Motes (Rooms)* is opened for mote selection which is shown in Figure 34. This frame lets the user selects up to five motes (rooms) individually or all motes (rooms) from the drop down menu. The drop down menus are filled automatically by retrieving list of the motes (rooms) from the database. In addition, *Building Managing Query & Analysis* tab has a message bar which informs the user about the cause of failed execution of the queries if there is any. The messages are usually for informing the user about selecting the wrong criteria, not selecting the right category or forgetting to select the motes (rooms).

3.5.8 Data query and analysis for network administrating

The users responsible for administrating the wireless sensor network are interested in retrieving the data from the database to analyze different aspects of the network

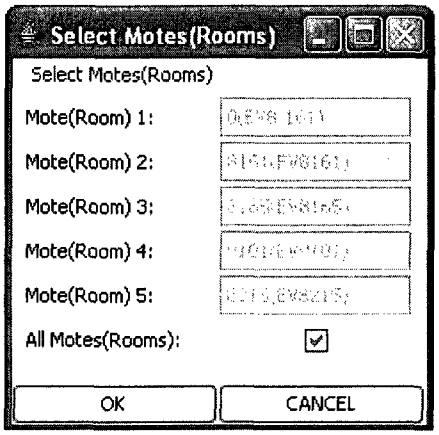


Figure 34: The graphical user interface for selecting motes (rooms) for data query and analysis.

such as the motes connectivity, the network's reliability and power usage of the motes. The *Network Administrating Query & Analysis* tab (shown in Figure 35) provides the interface for the user to query and analyze the data archived in the database. In this tab, first, the user has to define the period of time in which he/she wants to analyze the data. Then, the user can select one of two categories (Chart or Table) for viewing analyzed data. The two categories are as follows:

Chart: The chart category is used for charting two types of data which are link quality and power. For link quality data type, the user charts the quality of the links from the selected motes to their neighbors in the defined period of time with defined intervals. For power, the user charts the power of the selected motes in defined period of time with defined intervals. The charts are shown in a separate frame. The charting frame for both data types has the same look, features and functionalities of the tab for real time link quality charting which is explained in

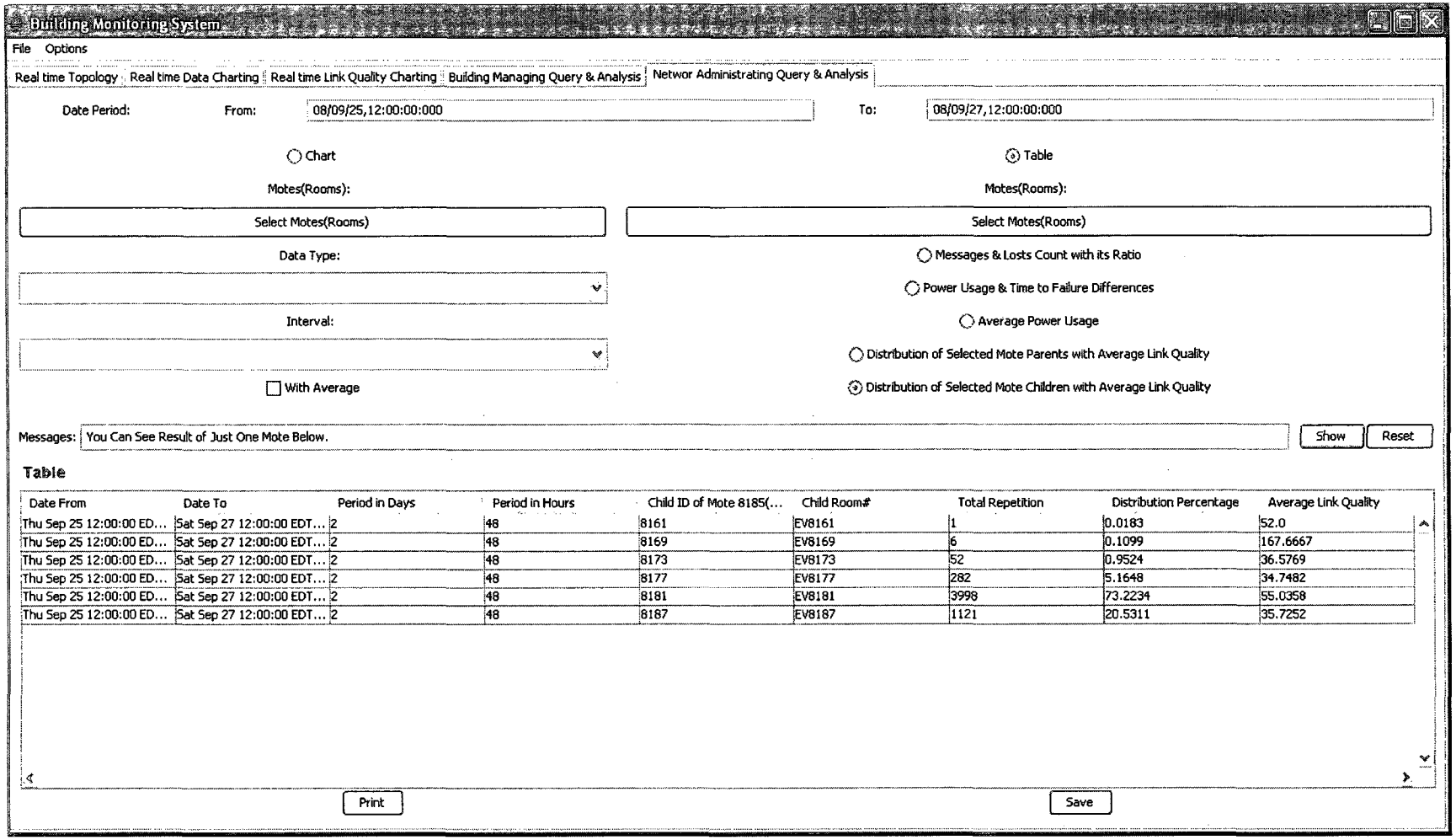


Figure 35: The graphical user interface for querying database and analyzing retrieved data by the users responsible for the network administrating

Subsection 3.5.6.

Table: The table category is used for showing the analysis of the retrieved data from the database in tabular format. For analysis, the user has to set the period of time, and then select the motes. Then, the user can select the desired type of analysis. The table will be shown in the bottom panel after clicking on the *Show* button. The tabular analysis can also be printed and saved as a file. Figure 35 shows different kinds of analysis that can be performed under table category.

In the *Network Administrating Query & Analysis* tab, whenever the user wants to select motes for analysis, he/she has to click on *Select Motes (Rooms)* button in appropriate category. The frame for selecting the motes (rooms) has the same look and functionalities as the one in *Building Managing Query & Analysis* tab. The *Select Motes (Rooms)* frame is shown in Figure 34. In addition, there is a message bar in *Network Administrating Query & Analysis* tab which is used for the same purpose as the one in *Building Managing Query & Analysis* tab.

Moreover, the generated charts and tables in *Network Administrating Query & Analysis* tab are shown and explained in Chapter 4.

Chapter 4

Data collection and analysis

In this chapter, first, we describe the deployment process of automated building monitoring system by wireless sensor network. Second, we analyze the system robustness and correctness along with network reliability and life time. Then, we explain the analysis of the collected data.

4.1 System deployment

We deployed and tested our system in the Engineering and Visual Arts (EV) building of Concordia University. Figure 36 shows the floor map of the 8th floor of the building; Rooms 9.101 and 9.105 in the 9th floor have been placed in the left top corner in order to have all rooms in the same picture. In reality, these two rooms are placed exactly over rooms 8.101 and 8.105 in the 8th floor.

We monitored 26 rooms in the 8th floor and 2 rooms in the 9th floor. We

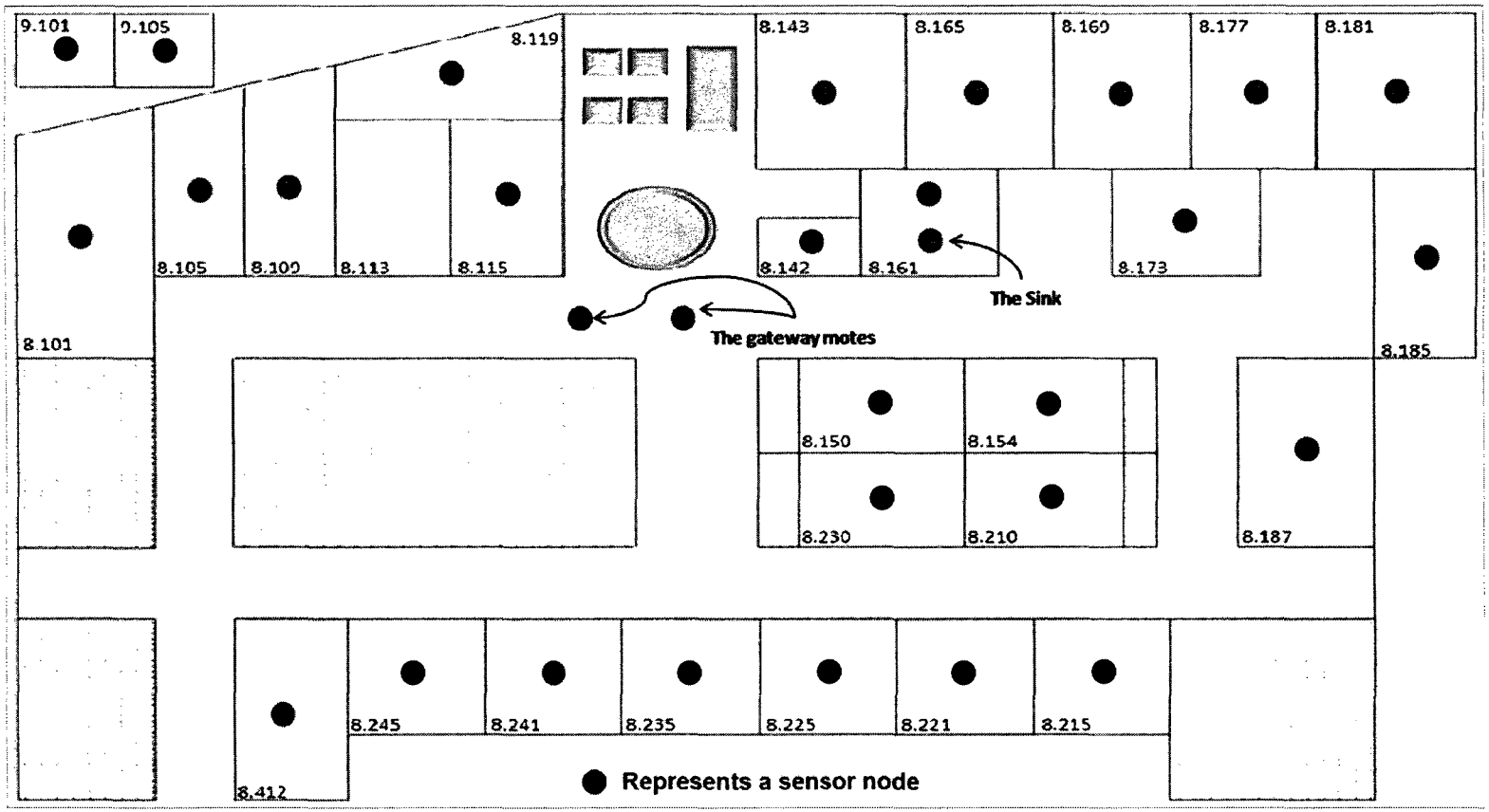


Figure 36: Floor map

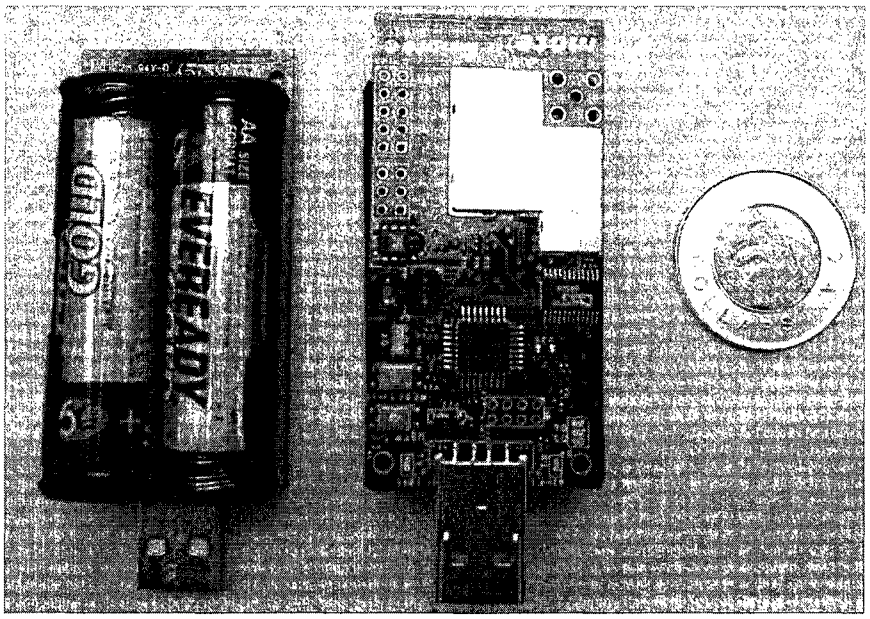


Figure 37: Tmote Sky mote (the 2$ coin is placed alongside to give an idea of the actual size of the mote)

programmed 31 Tmote Sky motes to form our wireless sensor network. Figure 37 shows one of the Tmote Sky motes that were used in our system. One of the motes was used as the sink and was placed in room 8.161. The sink was connected by the USB port to the PC on which the gateway/server was running. Twenty eight of the motes were placed in the rooms of the 8th and 9th floor. Two of the motes were used as the gateway motes in our wireless sensor network and were placed in the hallway of the 8th floor. The gateway motes were used to keep the whole network connected. Without using the gateway motes, the motes in top left of the floor map, which are shown in Figure 36, were disconnected from rest of the network due to the long distance they have from the nearest mote.

Each mote id was set according to the room number in which it has been placed

except the sink and gateway motes. For instance, the id of the mote placed in room 8.161 was set to 8161. The id of the sink was set to 0 and the id of the two gateway motes were set to 1 and 2.

For avoiding interference between the motes radio frequency and WLAN already working in the building, the radio channel of the motes were set to 26 working at radio frequency of 2.480 kHz. The features and specifications of the motes' radio transceiver are explained in Subsection 3.3.1. In addition, the power index of all the motes was set to 10, which equals -8dBm. This transmission power enables the motes to communicate with other motes at a distance of 8 to 10 meters. We chose the lowest possible transmission power for the motes to enable the motes to make reliable and robust multi-hop communication to the sink while considering energy conservation.

Each mote (except the sink and gateways) was placed over a lamp frame in its room, in such a way that the side of the board with sensors (not the battery side) was facing the ceiling. Figure 38 shows the mote placed over the lamp frame in room 8.161. As explained in Subsection 3.3.4, the mote's light sensors have to be placed close to the lamp's light and away from the direct sunlight to be able to sense the flickering of the light generated by the lamps. This is the reason for the choice of the placement of motes. In addition, with this placement, readings of the humidity and temperature sensors were accurate and reflected the exact temperature and humidity in the rooms.

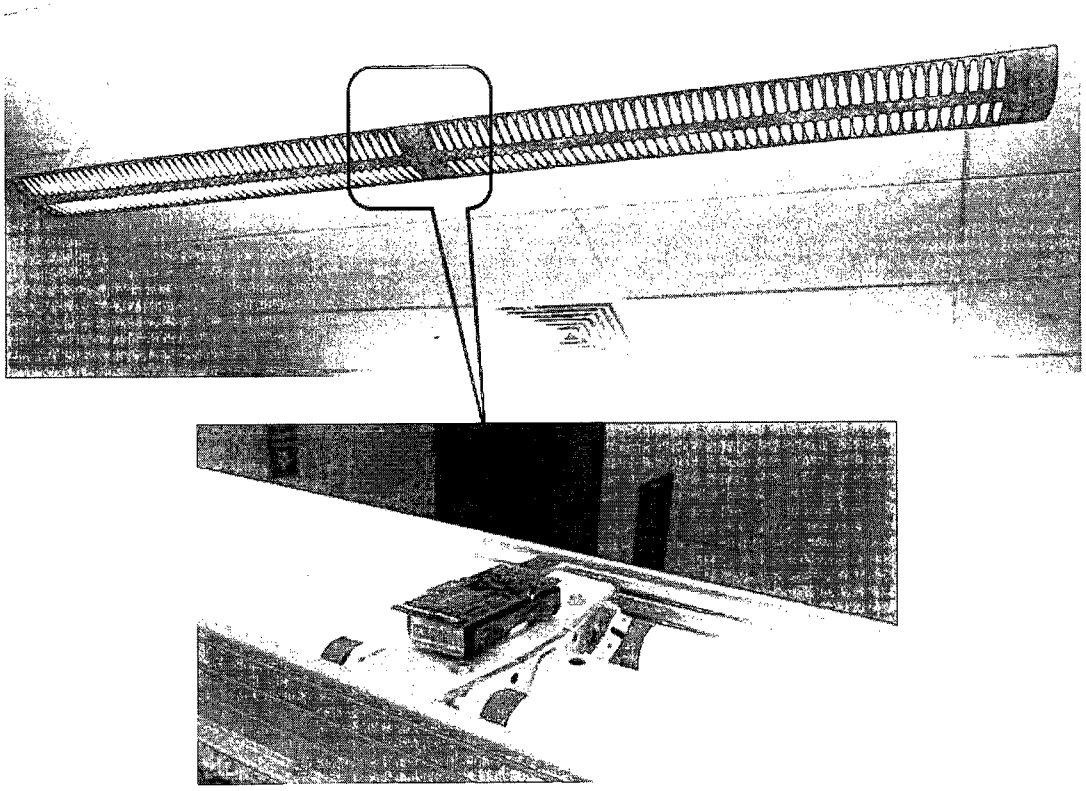


Figure 38: The placement of the mote over the lamps frame of room 8.161

We collected data and tested our system for 50 days (from October 1st, 12:01PM to November 20th, 12:01PM). The analysis of the collected data and performance of the system are explained in the rest of this chapter.

4.2 System analysis

Since there is no other automated building monitoring system using wireless sensor network, we cannot validate our system by comparing to other existing tools or research. However, we discuss the system correctness and robustness, and network reliability and life time in subsequent subsections.

4.2.1 System correctness

We checked the correctness of the data in our system manually or by use of other tools. For instance, for checking the correctness of reported temperature and humidity readings by all motes in the network, we compared the reported readings with manual readings taken using a La Crosse Technology thermometer in every room at different times. Similarly, for checking the correctness of reported lamp status, we checked the status of the lamps in all rooms at different times of the day. The mentioned methods were used for checking the correctness of the reported data during the collection period. Beside that, we checked and tested the correctness of every sensor and reported readings individually before deploying the motes.

4.2.2 System robustness

During the 50 days of data collection, the gateway/server and end user application ran in an uninterrupted fashion. The system successfully handled different types of exceptions such as bad received messages and interrupted server/client connection. The system can also detect intrusions and unexpected movement of the motes in wireless sensor network. For intrusions, the end user application can detect messages from unexpected motes and alerts the end user. For unexpected movement of the motes, the end user application consults each mote's neighbor list and informs the end user in case of any major change. However, these features were not tested.

4.2.3 Network reliability

Each mote sends a message every 30 seconds to the end user in our system. Therefore, the end user application is expected to receive 144,000 messages from each mote and 4,464,000 messages in all during the 50 days of data collection. The number of received messages increases with the generation of the messages by the motes for alerting the end user, since the alerting messages are generated more frequently (every 5 seconds) than regular messages. The cases where the system generates messages for alerting the end user are explained in Subsection 3.3.3. During the testing period, no critical situation happened in the building rooms. Therefore, there were no alerting messages from the motes.

Figure 39 shows the ratio of successfully received and lost messages to the total expected number of messages for each mote in the network during the 50 days of data collection. From this figure, we can see that the loss ratio of all motes in 8th floor is less than 5%. With such low loss ratio for our wireless sensor network, we can conclude that this wireless sensor network is reasonably reliable for building monitoring. Furthermore, we can see from the Figure 39 that the motes with id 9101 and 9102 in 9th floor have high loss ratio of more than 20%. The reason is that the motes in 9th floor have links with low link quality to their neighbors in 8th floor due to thick layer of cement and metal combined between the floors. Therefore, it is not recommended to place the communicating motes in different floors of the building.

Furthermore, with high ratio of successful message delivery, we can also conclude that the network was well-connected without loops during testing period. However, we can analyze the connectivity of each mote to its neighbors by using the information of the links and their quality from each mote to its neighbors. This information is archived during the testing period in the link table in our database. For instance, Figure 40 shows the connectivity statistics of mote 9101 during the 50 days of data collection. We can see that mote 9101 selected mote 9105 as its parent about 56% of the time due to the good link quality to this neighbor. Also, the mote 8109 has been selected as its parent just in 10% of the time due to its bad link quality. Recall that lower the link quality indication is, better the actual

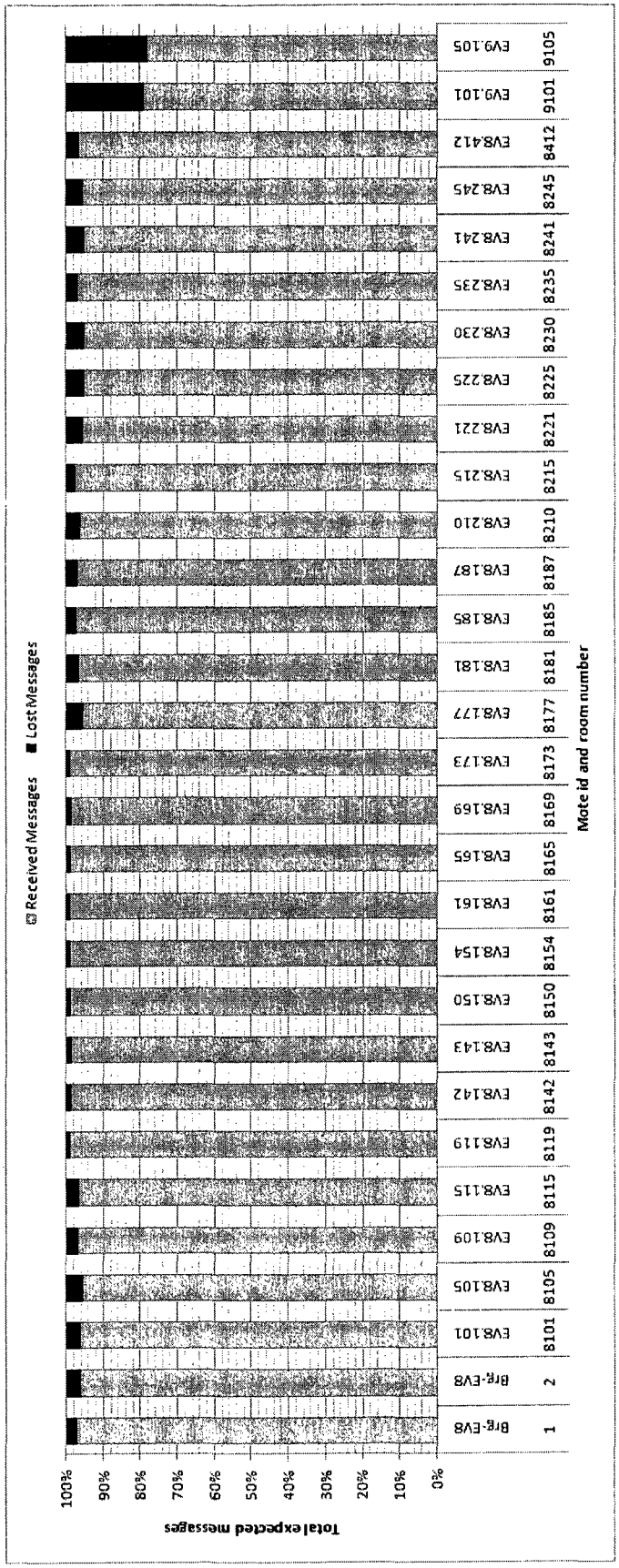


Figure 39: Ratio of successfully received and lost messages to total expected messages for each mote in the network

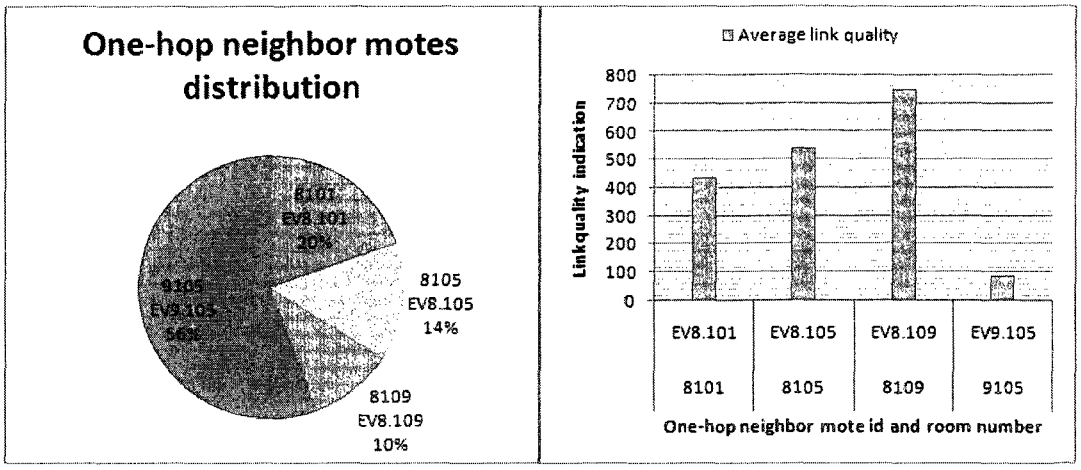


Figure 40: One-hop neighbor motes distribution and average link quality of mote 9101 in room 9.101

link quality is. From the average link quality of mote 9101 to its neighbor motes in Figure 40, we can conclude that the mote 9101 link quality to all of its neighbors in 8th floor is very low and this caused the high ratio of the lost messages for mote 9101, which is shown in Figure 39. Furthermore, Figure 41 shows connectivity statistics of mote 8210 in 8th floor during the 50 days of data collection. This mote has good link quality to its neighbors and has less than 5% loss ratio. This figure shows that worst link qaulity of mote 8210, which is to mote 8187, has almost the same average link quality as best link quality of mote 9101 which is to mote 9105.

Finally, the delay and processing time of receiving messages from the motes to the end user application is very low in this system. The interval of generating messages by the motes in the system is 30 seconds and the average interval time of the received messages from all motes during the testing period was 30.5 seconds.

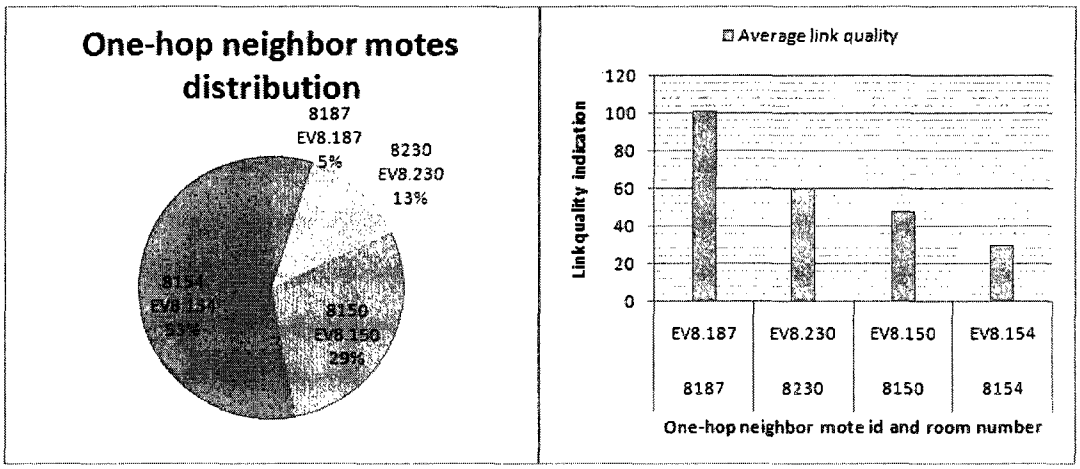


Figure 41: One-hop neighbor motes distribution and average link quality of mote 8210 in room 8.210

4.2.4 Network lifetime

As explained in Subsection 3.3.6, a duty cycle of 5% would enable motes to be functional for 107 days. At the end of 50 days, therefore we expect the motes to have used up to 50% of their power source. Figure 42 shows the remained and used power of all motes in our network at the end of the 50 days of data collection. As we can see from this figure, most of the motes except those on 9th floor have used about half of their power source during 50 days, which is about half of the expected life time of the motes. This validates the calculation of the lifetime and the correct functionality of the motes at the specified duty cycle.

The reason that the motes in 9th floor were consuming more power than the other motes was due to their bad connectivity to the motes in 8th floor. The poor connectivity caused these motes to not receive the synchronization beacon on time. Therefore, after their synchronization had been timed out, they kept their

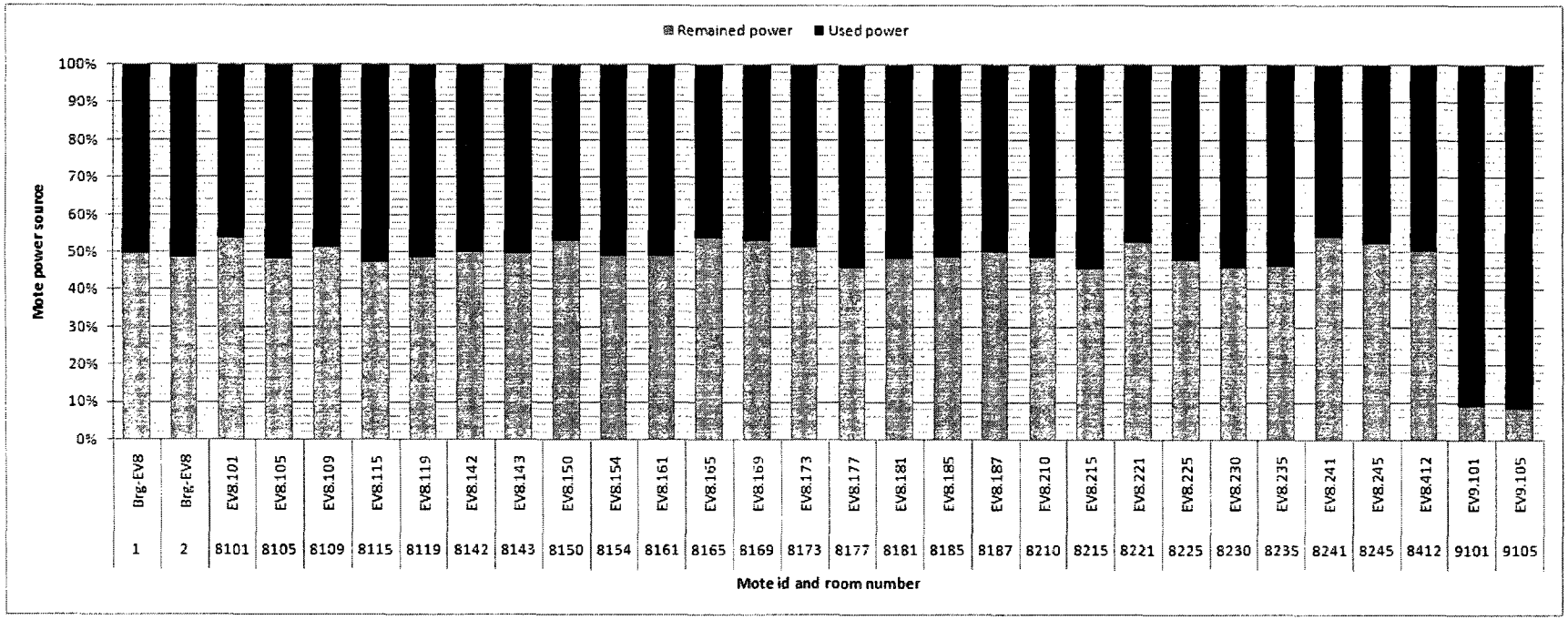


Figure 42: Remained and used power source of all motes

radio transceiver on in high power duty cycle (100% duty cycle) to receive the new synchronization beacon, thereby consuming more power.

4.3 Data analysis

During the 50 days of data collection, we collected the lamp status (room occupancy), temperature, humidity and brightness of the rooms. In this section, we analyze the collected data from all motes except the sink and the gateways.

The building in which we have tested our system has an automatic system for turning off the cooling, heating and ventilation system as well as the lamps of the rooms when there is no motion detected in the room. In the other words, when someone steps in the room the lamp, heating or cooling, and ventilation of the room turns on automatically based on the signal from the motion detector in the room. When no motion is detected for the period of 15 minutes, the lamps and other systems get turned off to conserve energy.

4.3.1 Lamp status (room occupancy) data analysis

Figure 43 shows the lamp status (room occupancy) statistics of all rooms during the testing period. From this figure, we can see that some rooms such as 8.412 and 9.101 were rarely used. In addition, we may conclude from Figure 43 that room 8.173 and 8.101 were occupied most of the time. However, we checked these rooms and we figured out that while room 8.101 is mostly occupied, the room

8.173 motion detector does not appear to shut off the lamps in this room, which are always on, unless manually turned off. Therefore, the correct occupancy of the room 8.173 cannot be deduced from our data. Also in Subsection 4.3.3, we explain how the analysis of the temperature and humidity data with lamp status can determine whether or not the motion detector in each room is functioning correctly.

4.3.2 Brightness data analysis

With the analysis of Brightness data, we can check whether each office has the necessary light provided by the lamps. In addition, we can figure out about the lamps that are not functioning any more by detecting changes in brightness level over time. Figure 44 shows the minimum and maximum brightness in all rooms when the lamps are on. From this figure, we can see that the minimum brightness in rooms 9.105 and 8.241 during the testing period was less than the required standard brightness for office work. The standard required brightness in each room for office work is at least 500 lx. However, the maximum values in both rooms were high enough to meet the standard. Therefore, we checked the lamps of these rooms and we figured out that one lamp in each room had been malfunctioning. In addition, we can see from this figure that the maximum of some rooms such as 8.101 and 8.105 are very high due to the daylight in these rooms through their windows.

Figure 45 shows the brightness level from 8:25AM to 2:49PM of October 2nd in

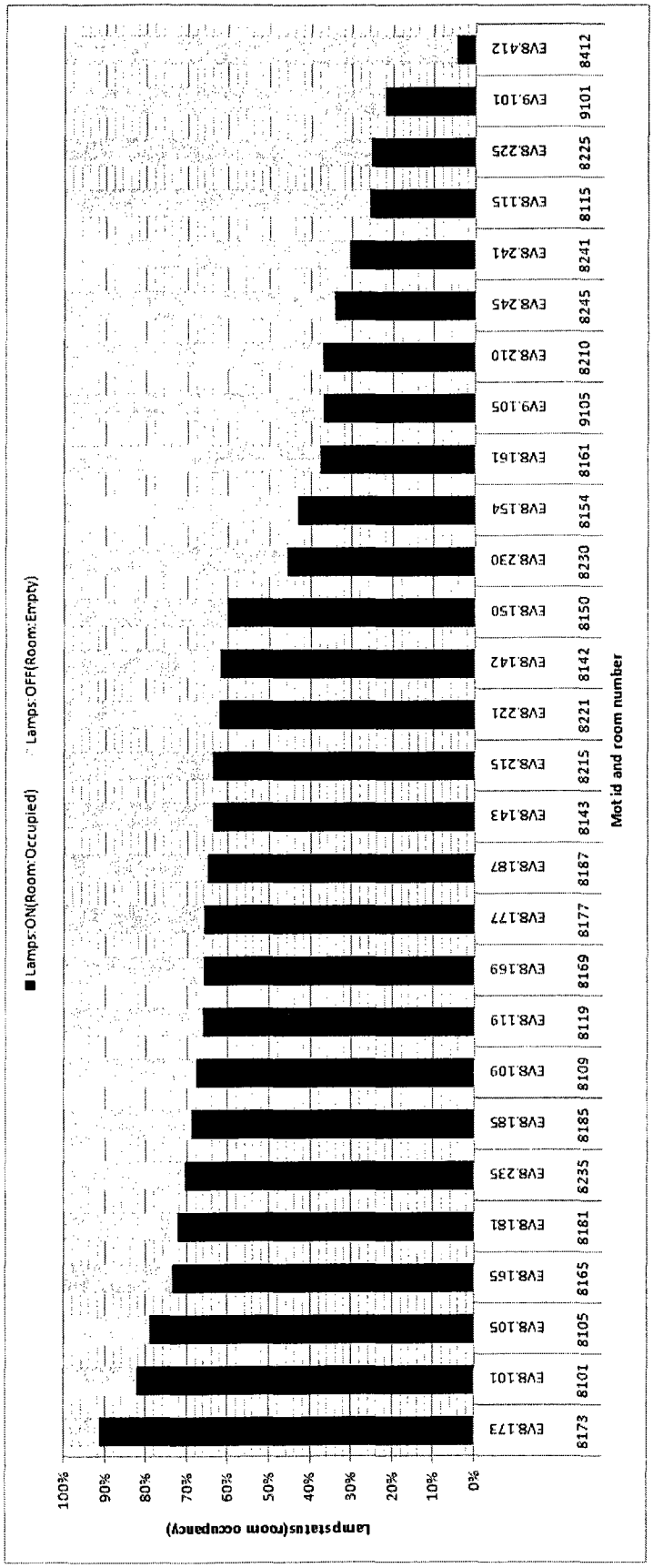


Figure 43: Lamp status (room occupancy) statistics during the 50 days of testing period

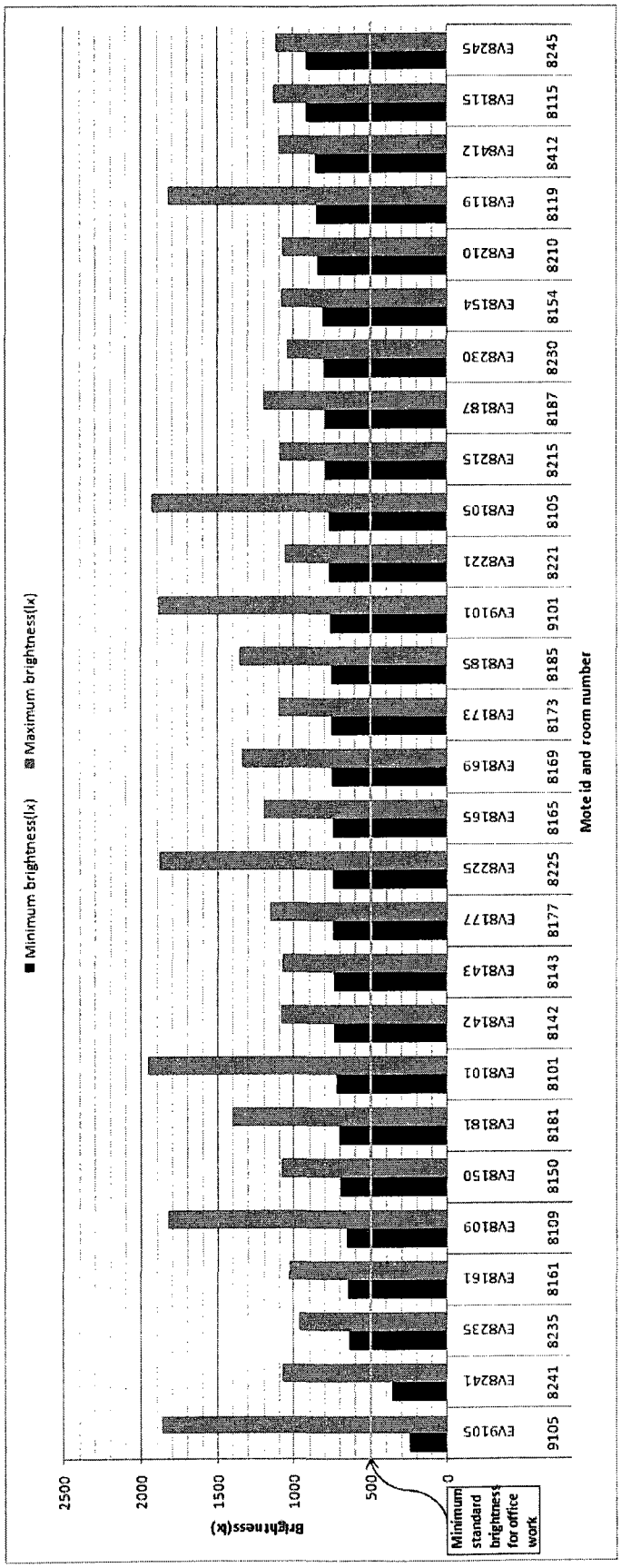


Figure 44: Minimum and maximum of the brightness in all rooms when the lamps are on

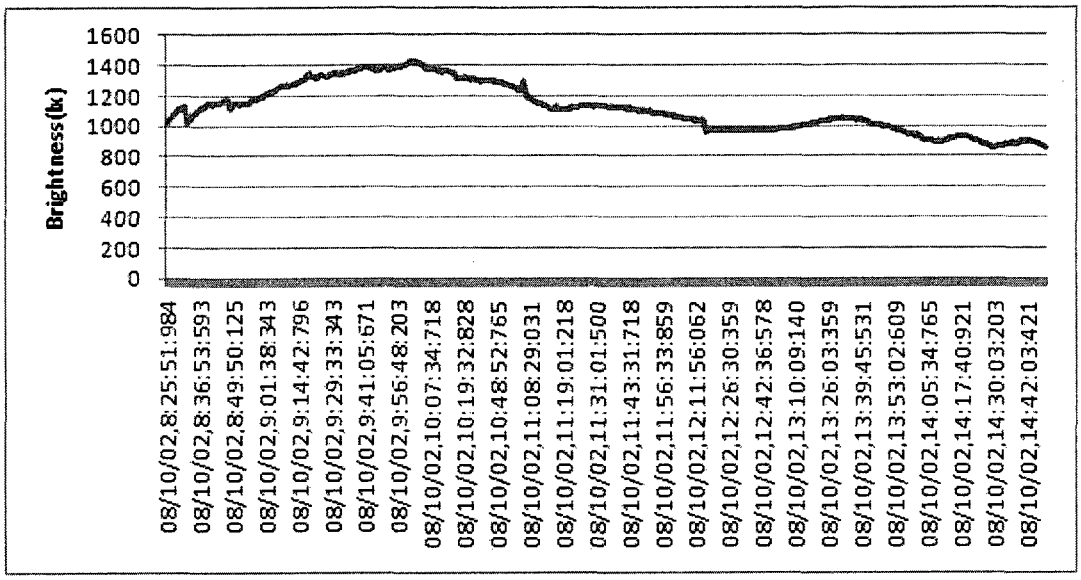


Figure 45: Brightness level in room 8.101 on October 2nd from 8:24AM to 2:49PM. Note that lamp status was off during this period.

room 8.101. The lamp status in this period is off. We can see from this figure that there is more than enough light in the room due to the daylight for office work, therefore turning the lamps on in the room automatically by the motion detector causes unnecessary energy consumption. This points to a limitation of using a motion detector exclusively as a method for energy conservation.

4.3.3 Temperature and humidity data analysis

Figure 46 shows the temperature and humidity changes in room 8.165 during one day. In this figure, the lamps are off when the lamp status curve is zero and the lamps are on when the lamp status curve is 70. When the motion detector detects any movement in the room, the lamps, heating and ventilation system are

turned on. When the heating and ventilation systems are off, in cooler weather, the temperature drops and the humidity rises in rooms.

By combining the lamp status data with the temperature and humidity data, we can analyze the functionality of the ventilation and heating systems. In addition, we can analyze the correctness of the lamp status data in relation to the room occupancy of the room. For instance, as we mentioned in Section 4.3.1, the motion detector in room 8.173 is not functional. Figure 47 shows the detailed temperature, humidity and lamp status data collected for room 8.173 during one day of the testing period. From this figure, we can see that even when the lamp status was always on, the temperature and humidity are adjusting due to the motions detected in the room. Therefore, the problem in this room is not related to the motion detector, but the problem is that the lamp switch is not reacting to the motion detector signals.

Figure 48 shows the minimum, maximum and average of temperature in all rooms when the ventilation and heating systems were on (when the lamps are on) during the 50 days of testing. Figure 49 shows the distribution of the temperature values of room 8.165 during the testing period when the ventilation and heating system were on. We can also have the same figures for humidity.

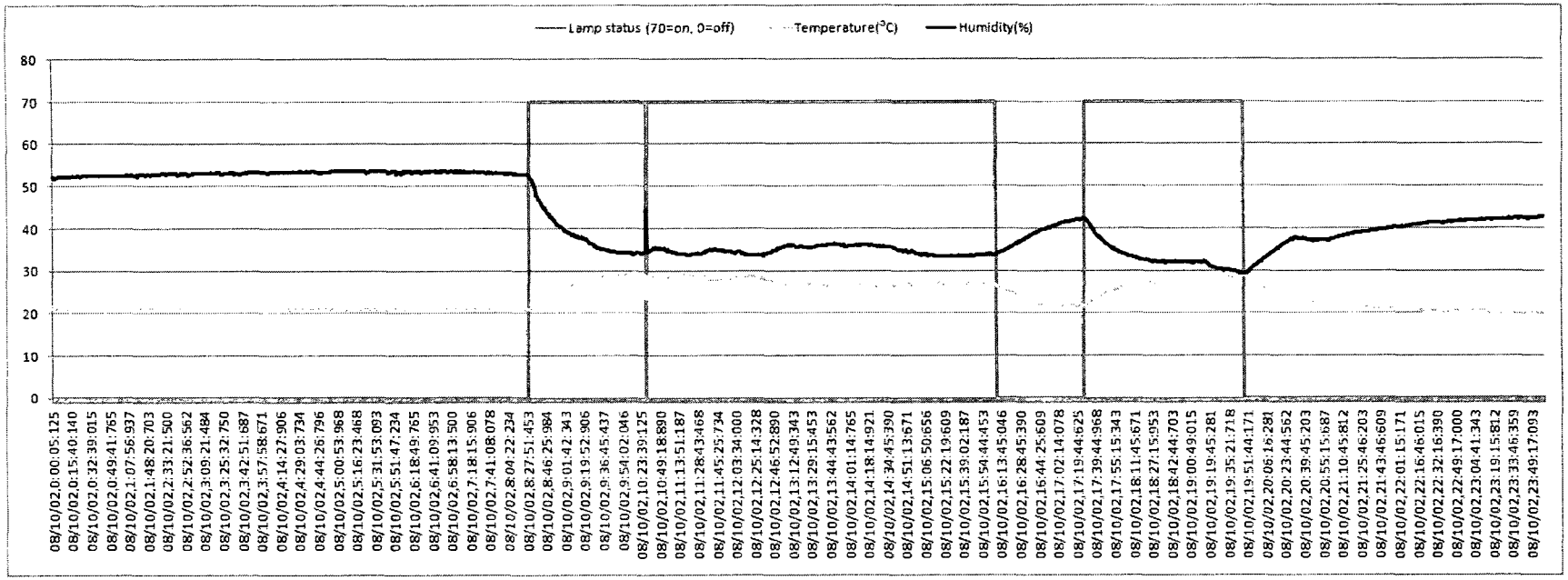


Figure 46: Temperature, humidity and lamp status changes in room 8.165 during one day of the testing period

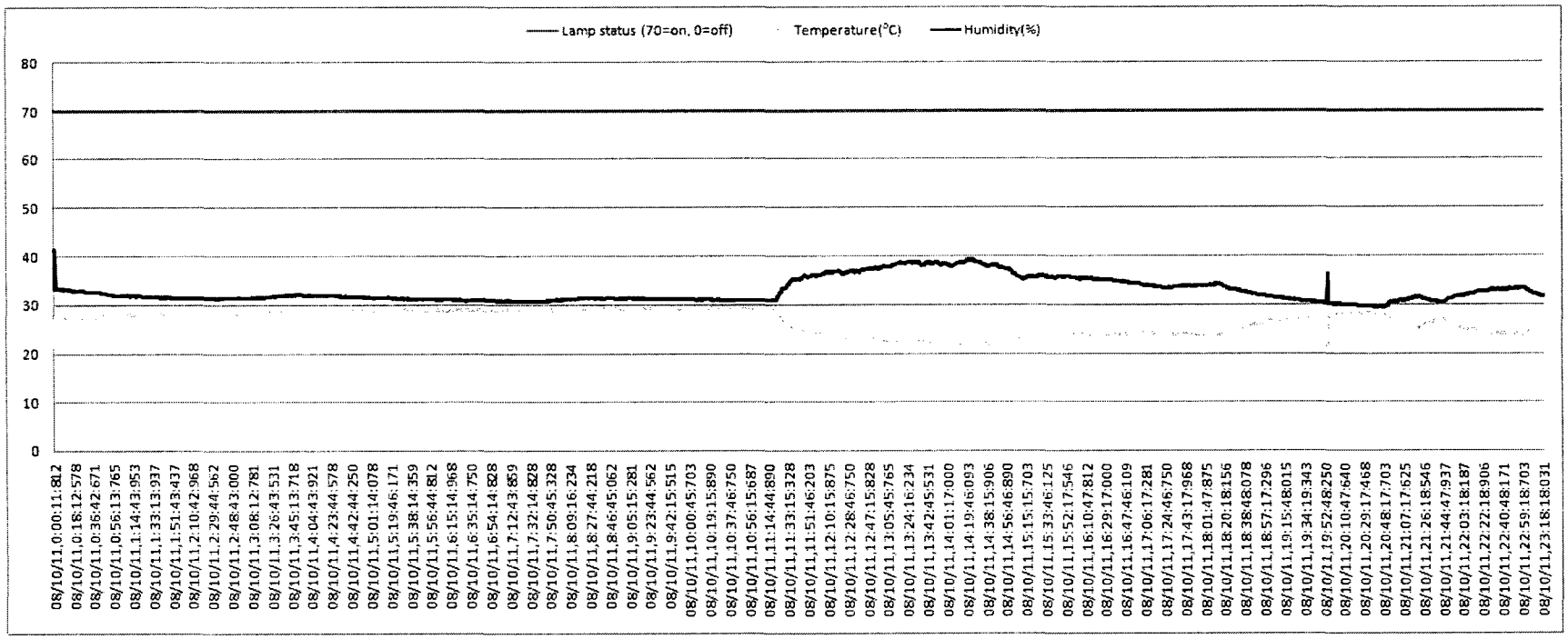


Figure 47: Temperature, humidity and lamp status changes in room 8.173 during one day of the testing period

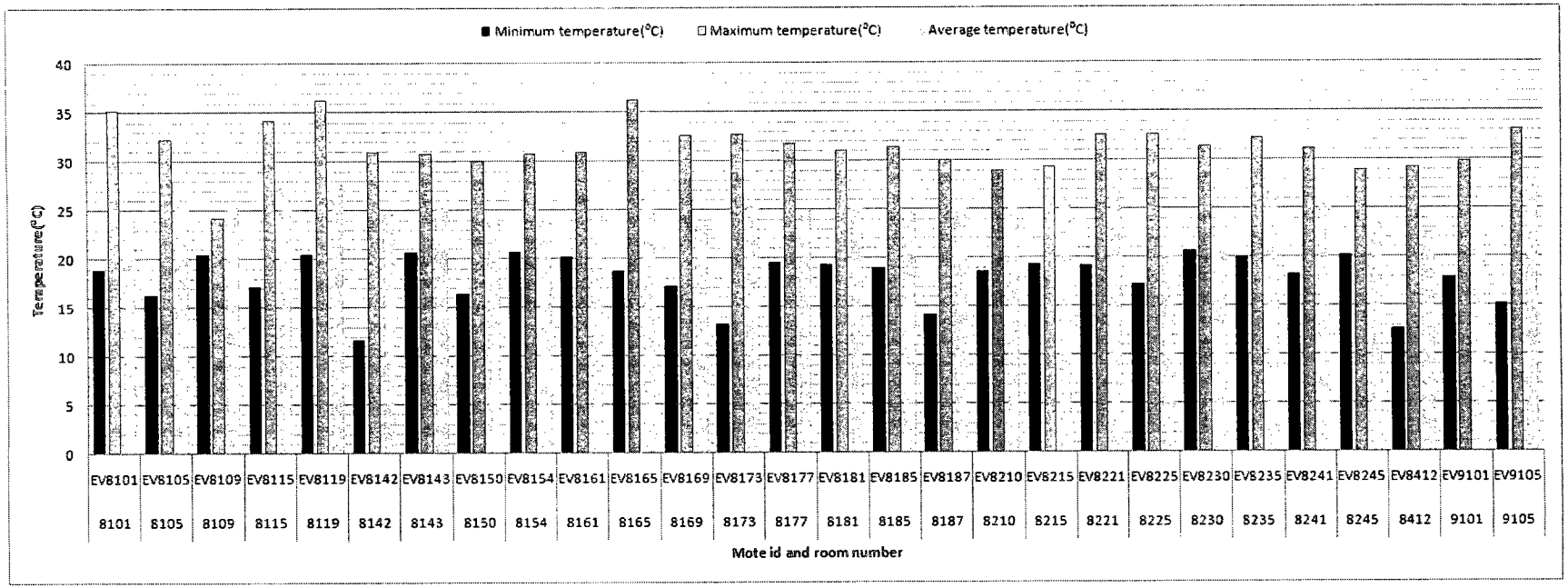


Figure 48: Minimum, maximum and average of temperature in all rooms when the ventilation and heating systems were on during the testing period

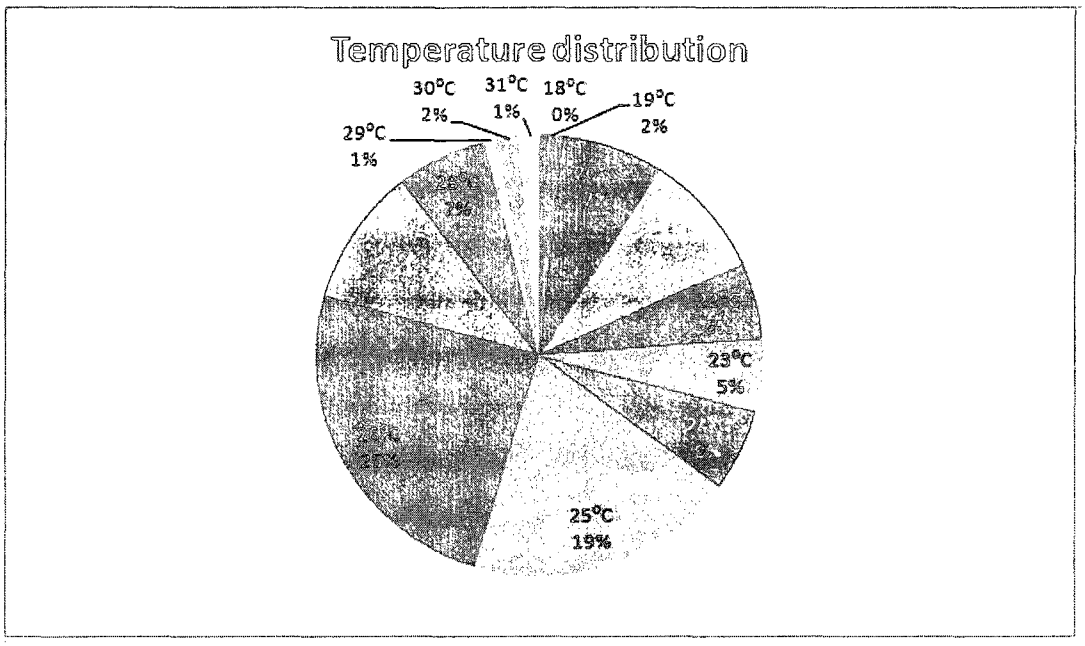


Figure 49: Distribution of the temperature values in room 8.165 when the ventilation and heating systems were on during the testing period

4.4 Discussion

In this section, we discuss the challenges involved in implementing the system as well as the extent and the limitations of the information obtained.

The first challenge in implementation is extending the life time of the wireless sensor network. As we explained in Subsection 4.2.4, motes are operational for about 100 days if they are in good communication range of each other and they are using a 5% duty cycle. However, it is challenging to increase the life time of the motes by using lower duty cycle and still fullfil the end user requirement such as having the most up-to-date data. The lifetime of nodes is also affected by the problem of poor connectivity as explained below.

The second challenge is connectivity between the motes in different floors. As we explained in Subsection 4.2.3, motes in different floors cannot communicate with each other due to the concrete barriers between the floors. Therefore, the network is not well-connected between the floors. For this problem, we propose the solution of placing one sink in each floor and making separate collection trees in each floor rooted at the sink placed in the same floor. In other words, one mote is placed in each room of the building. Each mote in a floor has a unique address (id). Two motes can have the same id as long as they are on two different floors. All motes in each floor have the same group id which is programmed in the motes at the same time with their ids. The group id for each floor is unique. This makes the motes form separate networks in different floors. Therefore, when there are many motes in the whole building and the motes in different floors can not communicate to each other with good link quality, the mentioned way of separation of the motes between each floor can make better quality of service and also aid energy conservation, which can further increases the lifetime of the motes.

The third challenge is massive data processing by the gateway/server and the end user application. We have used a commercial database and a multi-threading approach to meet this challenge. The massive data processing can also be solved by using hardware with higher capabilities in terms of memory and computation or by using different programming techniques such as direct hardware access instead of using operating system APIs.

There are different types of information that have been obtained from the deployment of our system. Watching the indoor environment condition of the building is the information that provides the end user with real time status of the room climate and lamp status such as the one shown in Figure 48. As Figures 49 and 44 show, the end user can also monitor and optimize the ventilation and lighting system by having the information extracted from the periodic report of climate condition and lamp status of each room. We have considered lamp status of each room as an approximation to room occupancy in this thesis: a room is occupied when the lamp is on and it is unoccupied when the lamp is off. However, this is not always true such as in room 8.173 as was explained in Subsection 4.3.1. Furthermore, the end user can also determine the performance of already existing building monitoring systems or diagnose individual building facility performance remotely by combining the data reported for different metrics such as humidity and temperature to derive new information as explained in Subsection 4.3.3. Finally, studying the possible energy conservation methods can be performed by the end user such as turning the lights on/off centrally for the rooms with enough light provided from daylight as shown in Figure 45.

Chapter 5

Conclusion and recommendations for future work

In this thesis, we proposed and developed a system for building monitoring using wireless sensor network technology. Even though during the last decade, there have been several research projects that have led to some improvements in different areas (subfields) of wireless sensor networks, there has not been enough focus on the application layer of this technology in building monitoring. In this thesis, we developed an automated building monitoring system using a wireless sensor network for monitoring climate, brightness and lamp status of the rooms in the building. By using the status of the lamps in the rooms, we monitor the occupancy of the rooms as well. Our system consists of three main subsystems: wireless sensor network, gateway/server and end user application. The wireless sensor network reports the

collected data for temperature, humidity and brightness and the calculated data, which is lamp status (room occupancy) to the sink while considering energy conservation by using low power duty cycle. The gateway/server forwards the received data from the sink to the end user application that is connected to it. In addition, the gateway/server archives the received data in a database for later retrieval and analysis. The end user application visualizes the network connectivity. It provides tools to view and search a mote's information. It also provides charts for analyzing the information based on the received data for two categories of users, namely the building manager and the network administrator. The application interprets the data from the database in order to analyze the building climate, room occupancy and brightness, and functionality of the heating, cooling and ventilation system of the building.

We are optimistic that this system provides a much simpler and more flexible system design than old-fashioned wired building monitoring systems. Our system allows for faster and easier installations at a lower cost and with fewer constraints associated with maintenance. Finally, our system provides more accurate and robust analysis of the information about building climate conditions and controlling systems as well as room occupancy. As explained in Section 4.4, the most important challenges encountered system implementation were extending the life time of the wireless sensor network, connectivity between the motes in different floors, and massive data processing by the gateway/server and end user application.

For future work, we believe that the system can be complemented by improving the routing algorithm to have guaranteed delivery for alert messages, having a localization algorithm in the network to track objects or staff in the building, aggregating data for situations with more than one mote in one room, implementing a dissemination algorithm for commanding and reprogramming the motes over the air in the network, decreasing the power consumption of the mote, making a system model for building monitoring applications, analyzing data automatically, and controlling the building heating, cooling, ventilation and lighting systems locally by motes.

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Appendix A

Installation guide

The automated building monitoring system using wireless sensor network consists of three subsystem which are wireless sensor network, the gateway/server and the end user application. For running the system, first the code has to be compiled and installed into the wireless sensor hardwares (motes). Second, the gateway/server has to be run while the sink is connected to the USB port of the computer and the computer is connected to Internet. Then, the end user application can be run to receive data from the gateway/server.

In order to compile and install the code on the wireless sensor hardware, the following steps should be performed:

1. Installing Boomrang software which includes TinyOS 1.x operating system, Cygwin tool and NesC programming language from www.moteiv.com.

2. Compiling the BMAppl application with command "make tmote lowpower,5"

in Cygwin command prompt.

3. Connecting each mote through USB port to the computer and program the mote with command "make tmote lowpower,5 reinstall,?" where ? is the id number of the mote in the network. Note that the sink has to be programmed with id 0.

In order to run the gateway/server, the following steps should be taken:

1. Installing J2SE 1.4 from java.sun.com.

2. Installing MySQL server 5.2 from www.mysql.com.

3. Connecting the sink with USB port to the computer.

4. Connecting the computer to Internet.

5. Executing the bin.bat file in "the gateway/server" folder to run the gateway/server.

In order to run the end user application, the following steps should be placed in order:

1. Installing J2SE 1.4 from java.sun.com.

2. Executing the bin.bat file in "end user application" folder to run the end user application.

3. Entering the IP address and port number of the computer on which the gateway/server is running and clicking on "Connect" button to start receiving the messages.

Appendix B

End user application and gateway/server design

In this part, we show the package diagrams and class diagrams of the end user application and the gateway/server. This appendix can be used as the documentation of the system and also for system maintenance in case of error or fault, system expansion for implementing a new set of requirements, or system adaptation to new operating systems, softwares or hardwares.

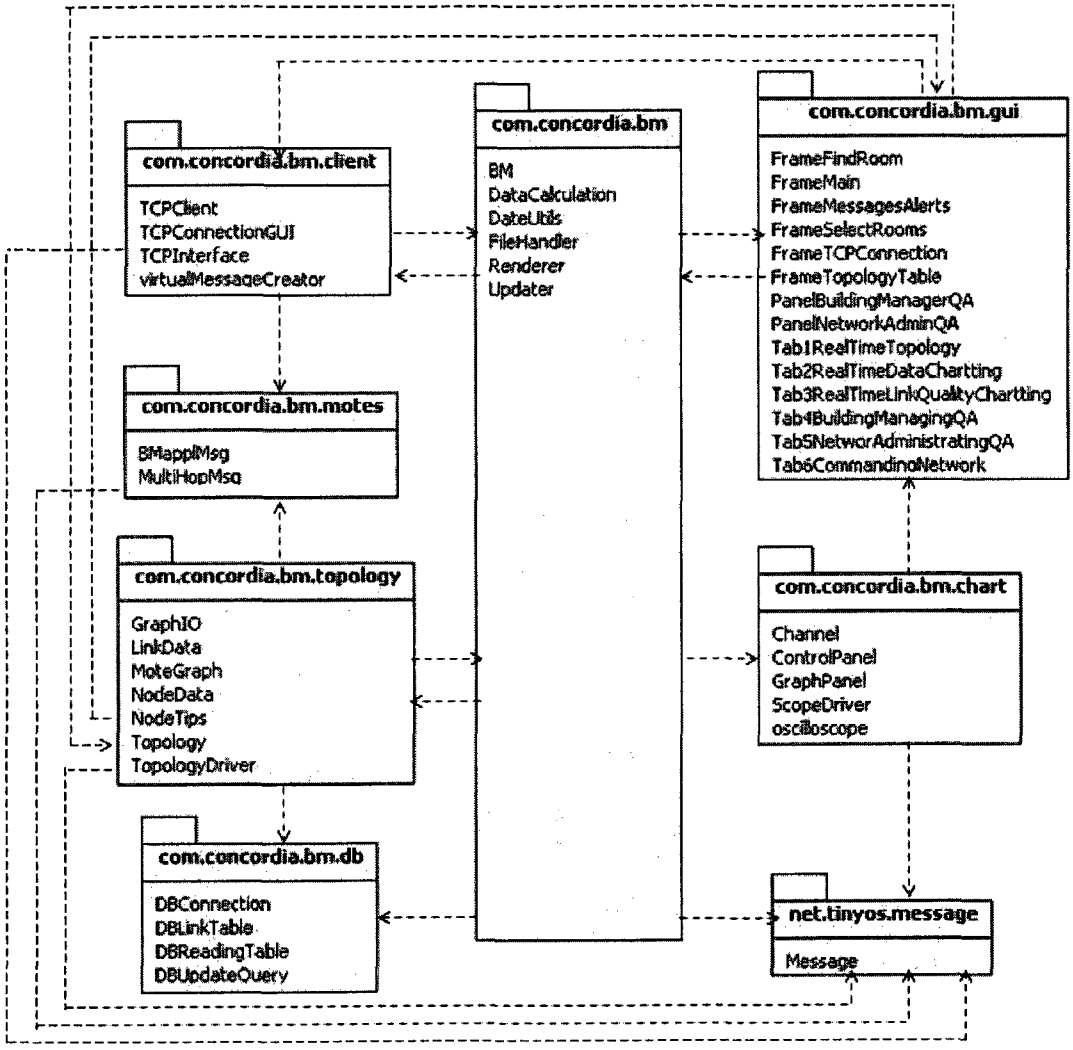


Figure 50: End user application

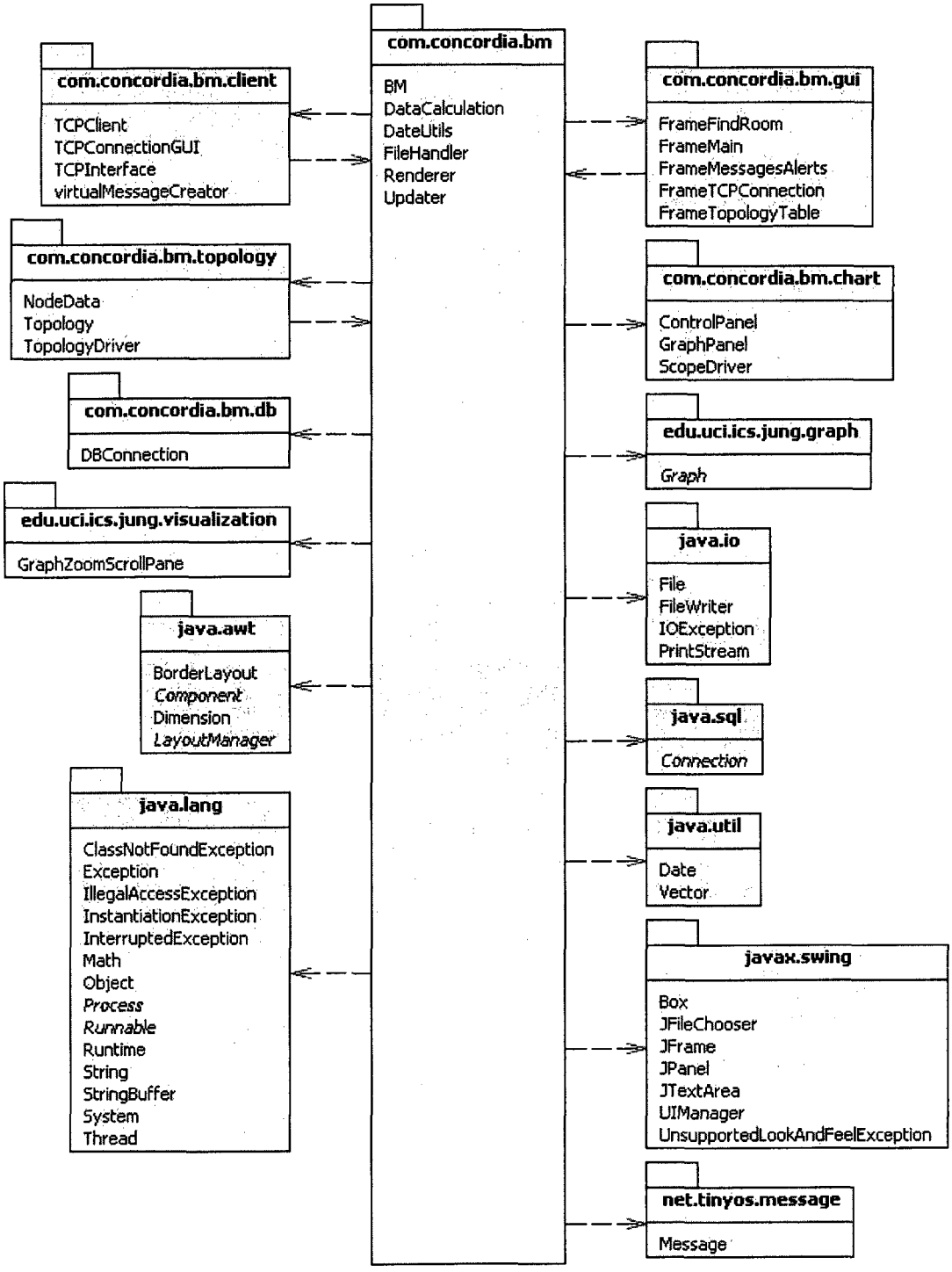


Figure 51: Package com.concordia.bm

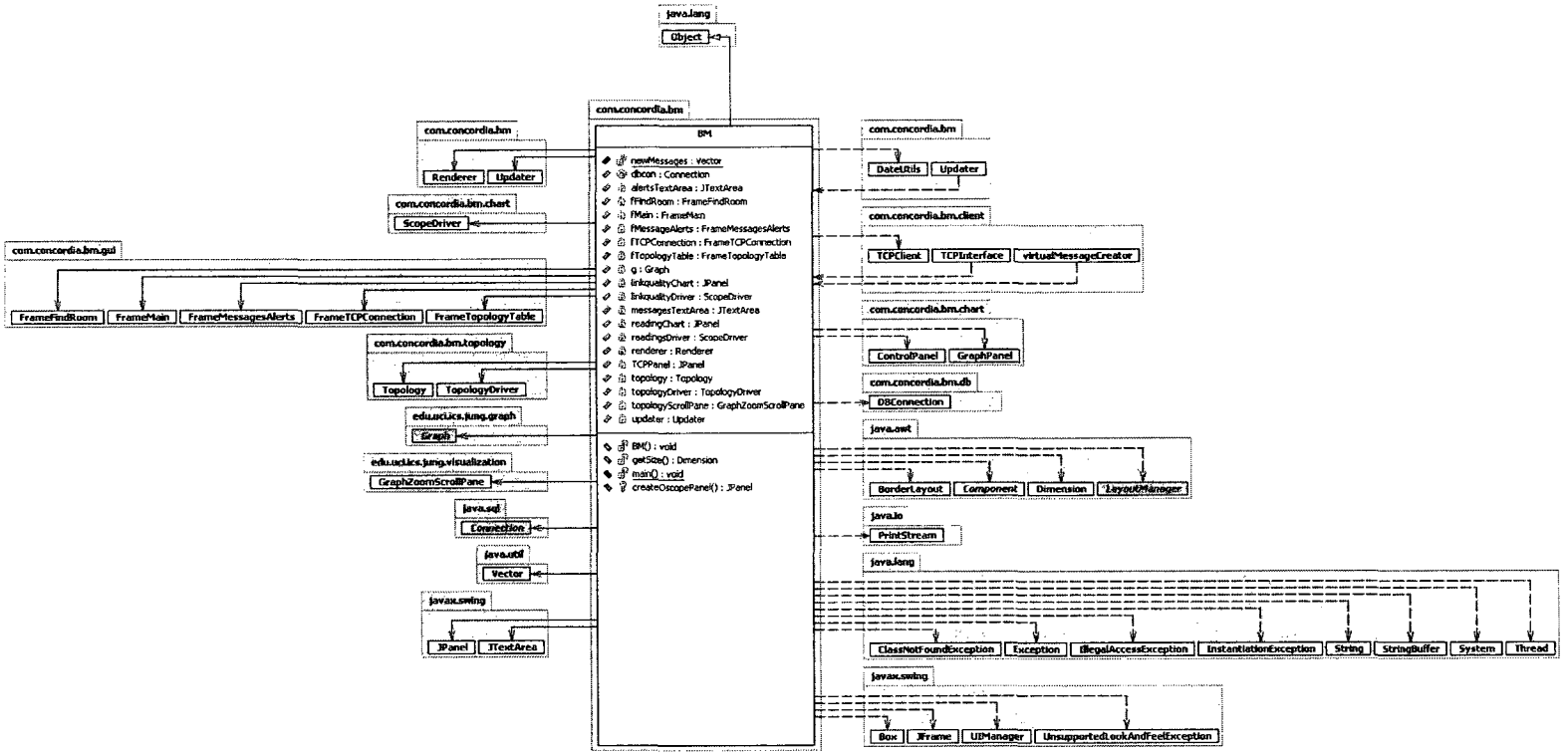


Figure 52: Class com.concordia.bm.BM

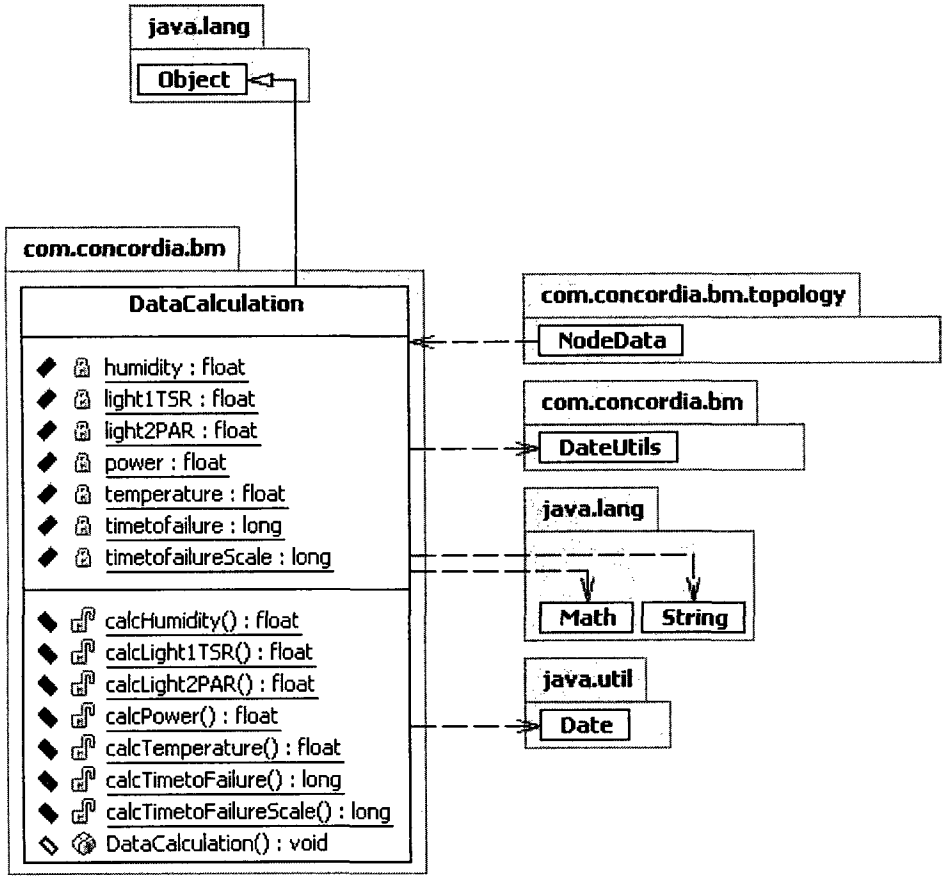


Figure 53: Class com.concordia.bm.DataCalculation

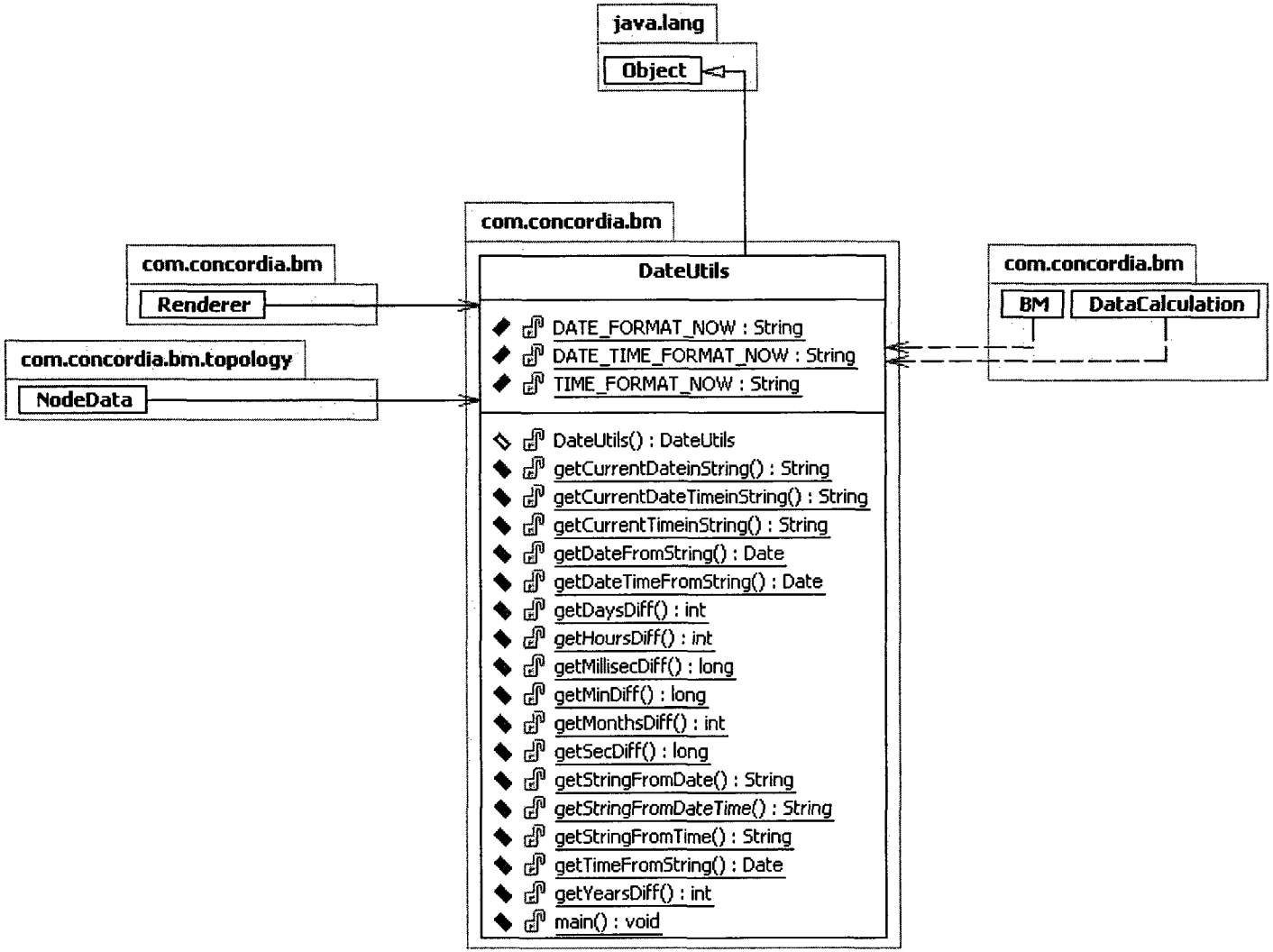


Figure 54: Class com.concordia.bm.DateUtils

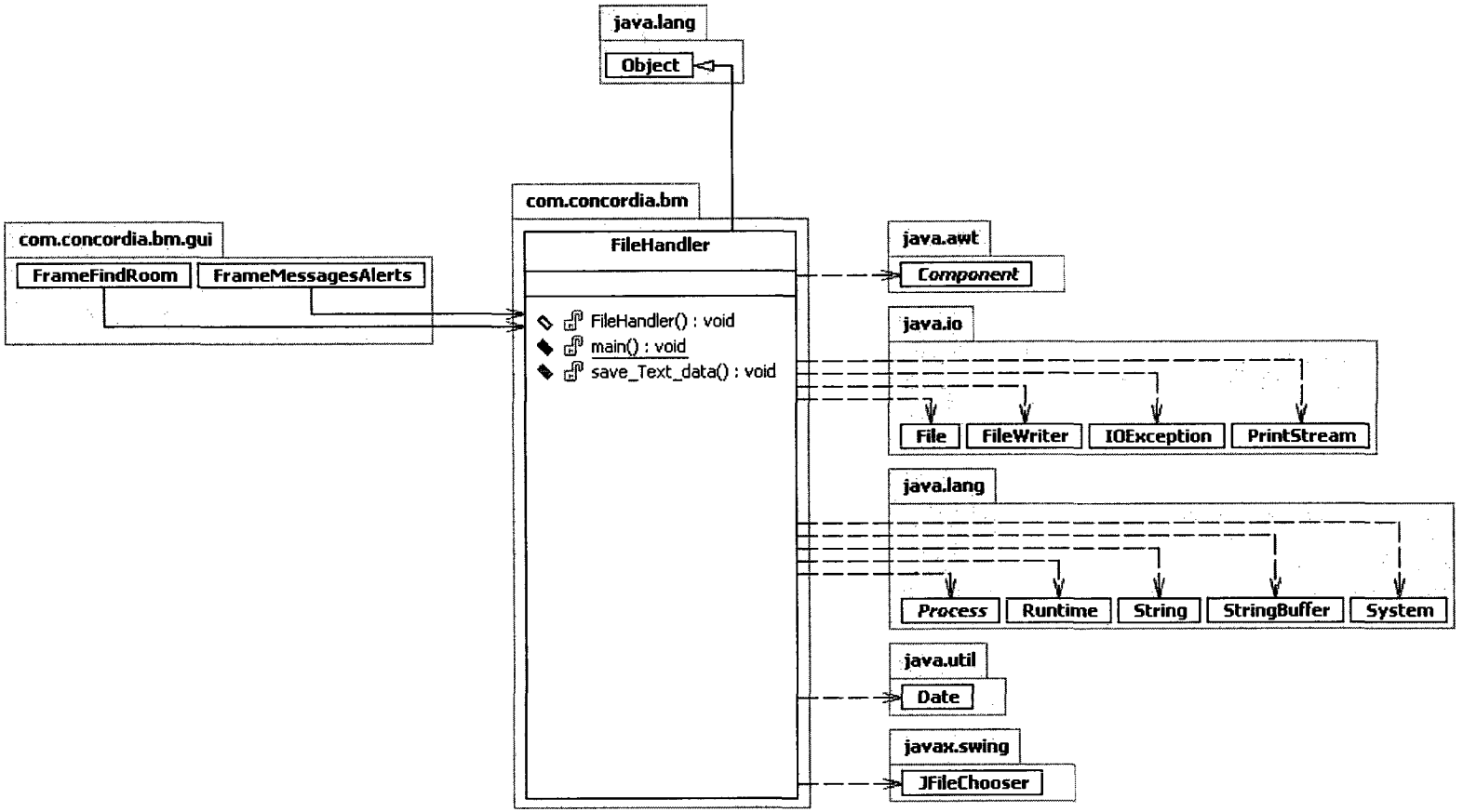


Figure 55: Class com.concordia.bm.FileHandler

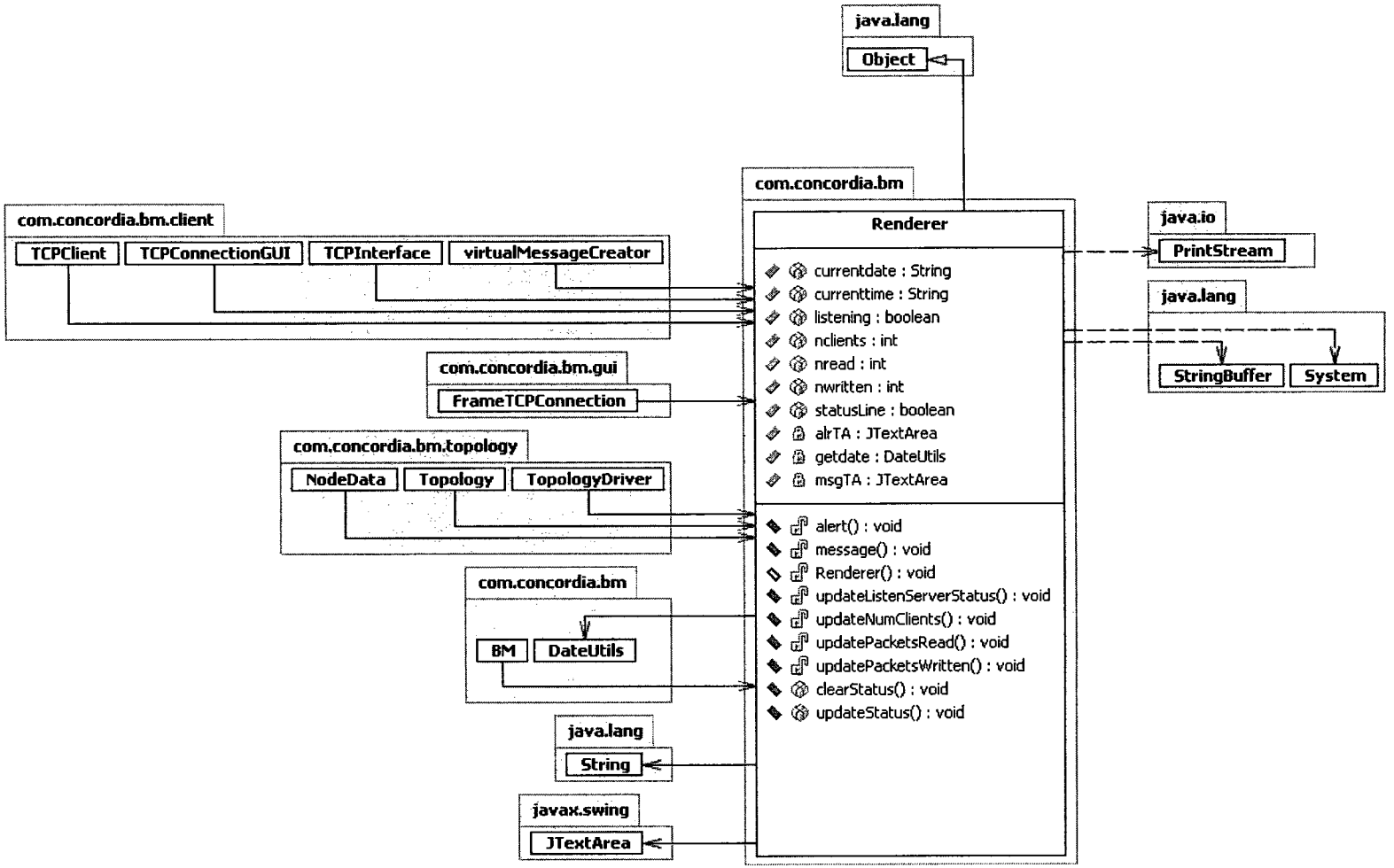


Figure 56: Class com.concordia.bm.Renderer

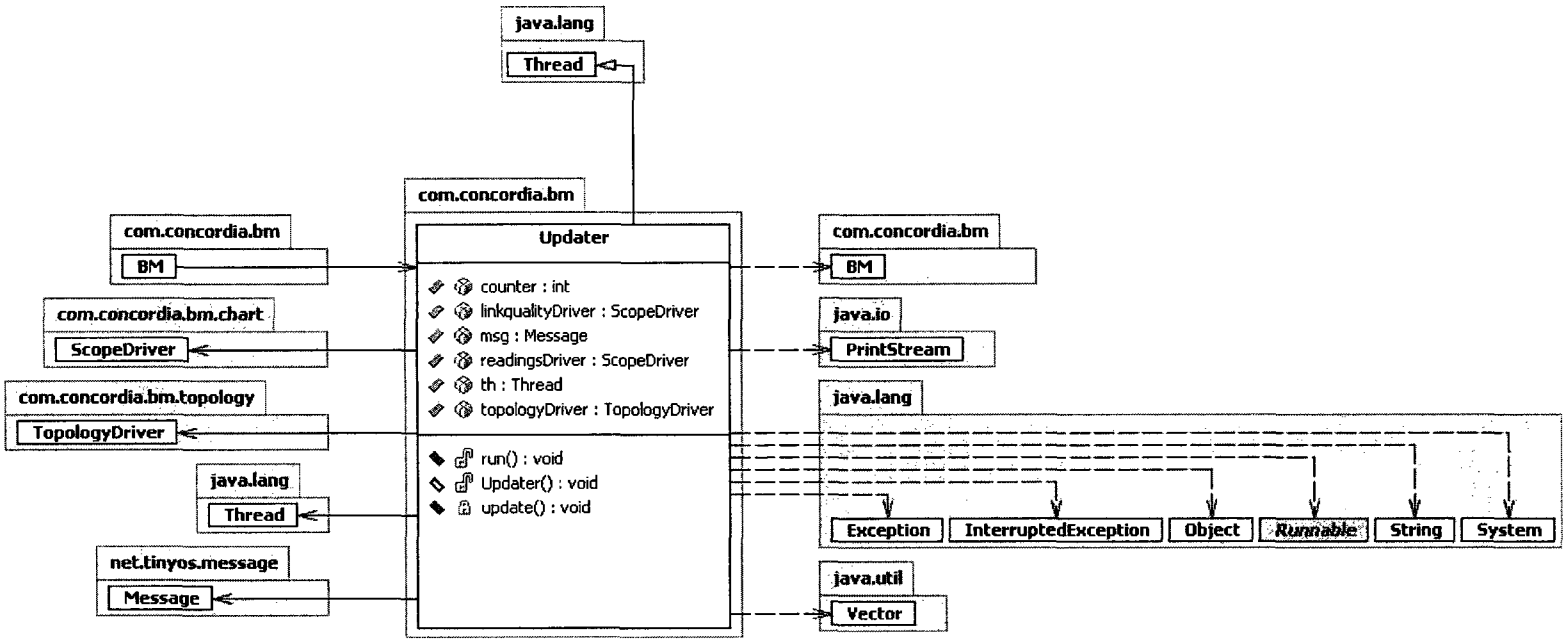


Figure 57: Class com.concordia.bm.Updater

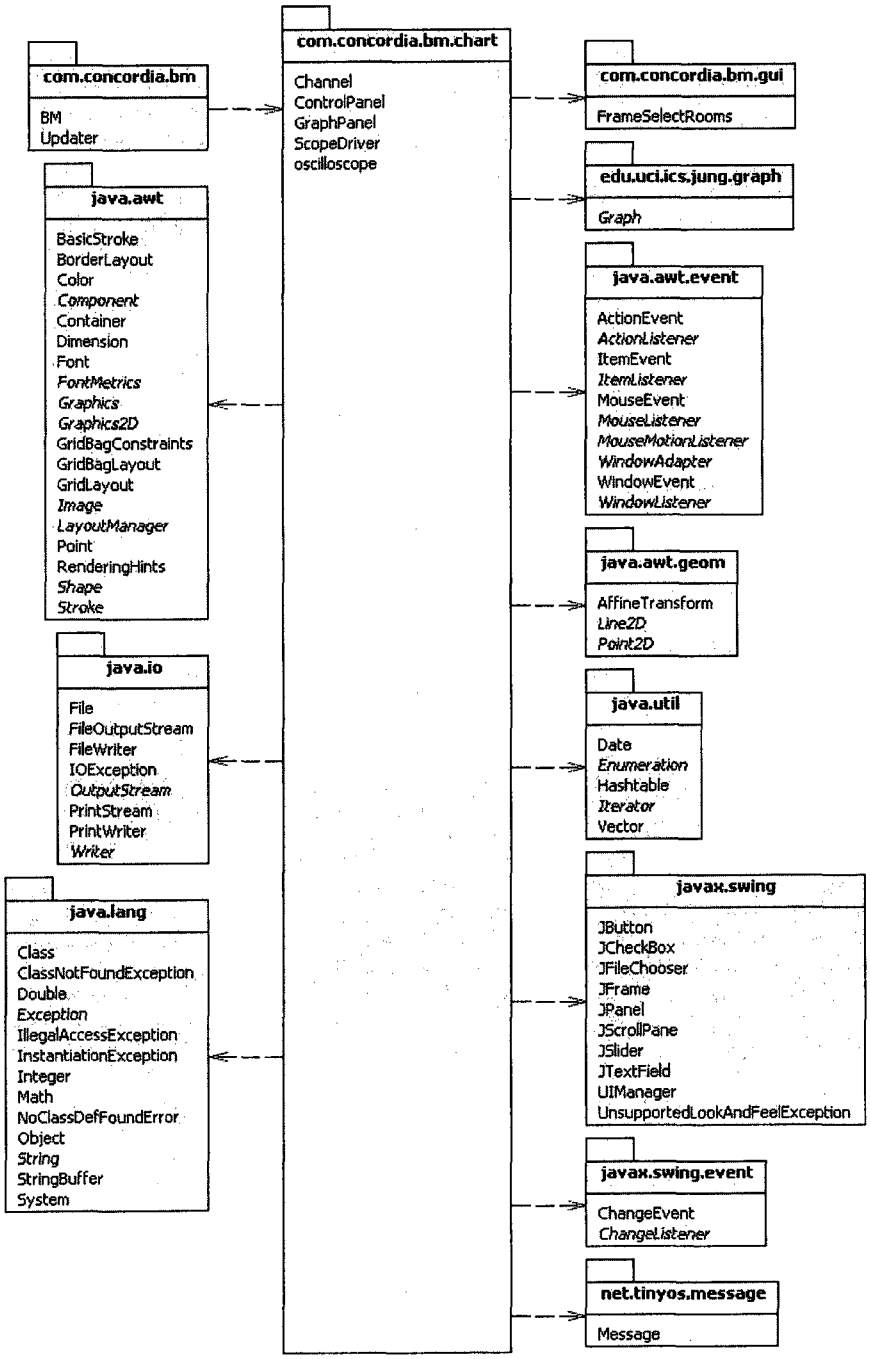


Figure 58: Package com.concordia.bm.chart

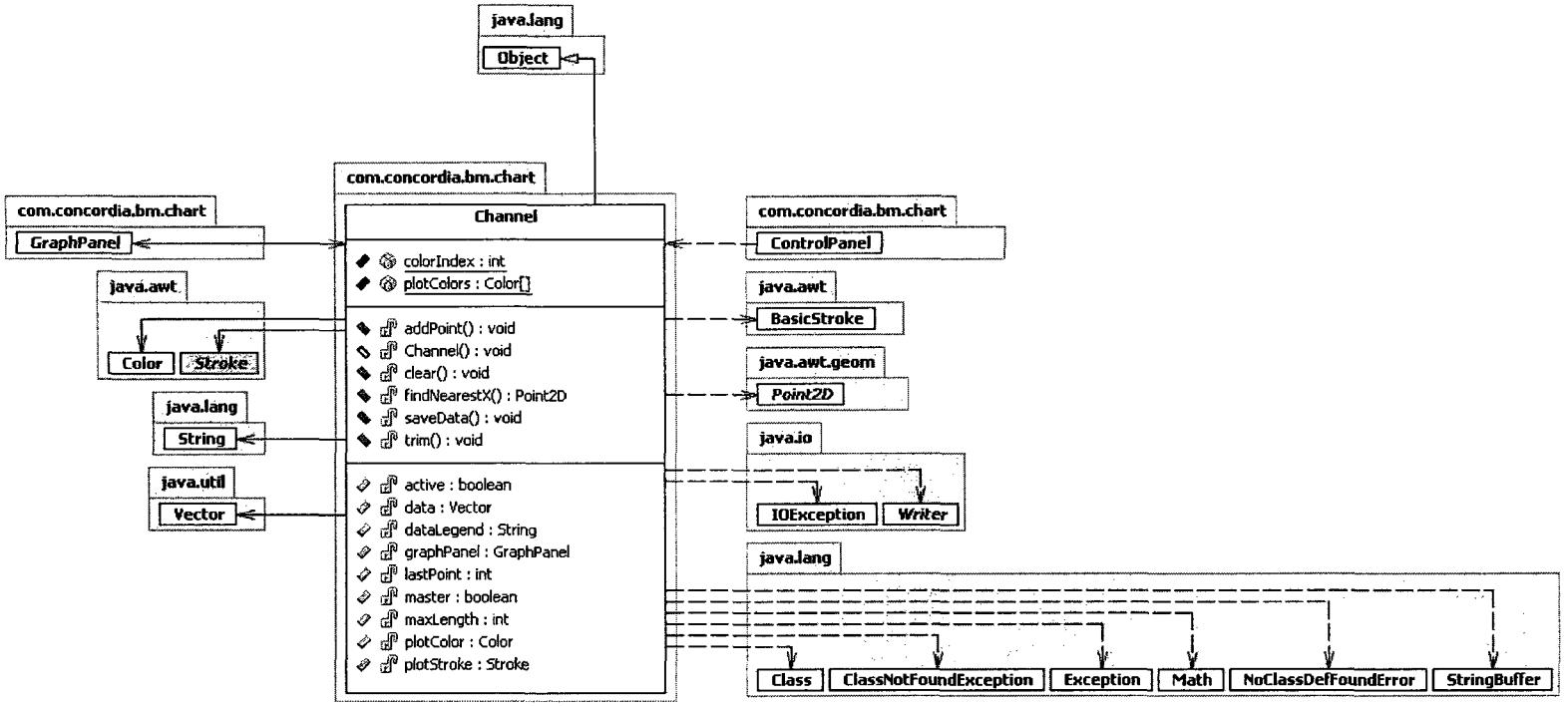


Figure 59: Class com.concordia.bm.chart.Channel

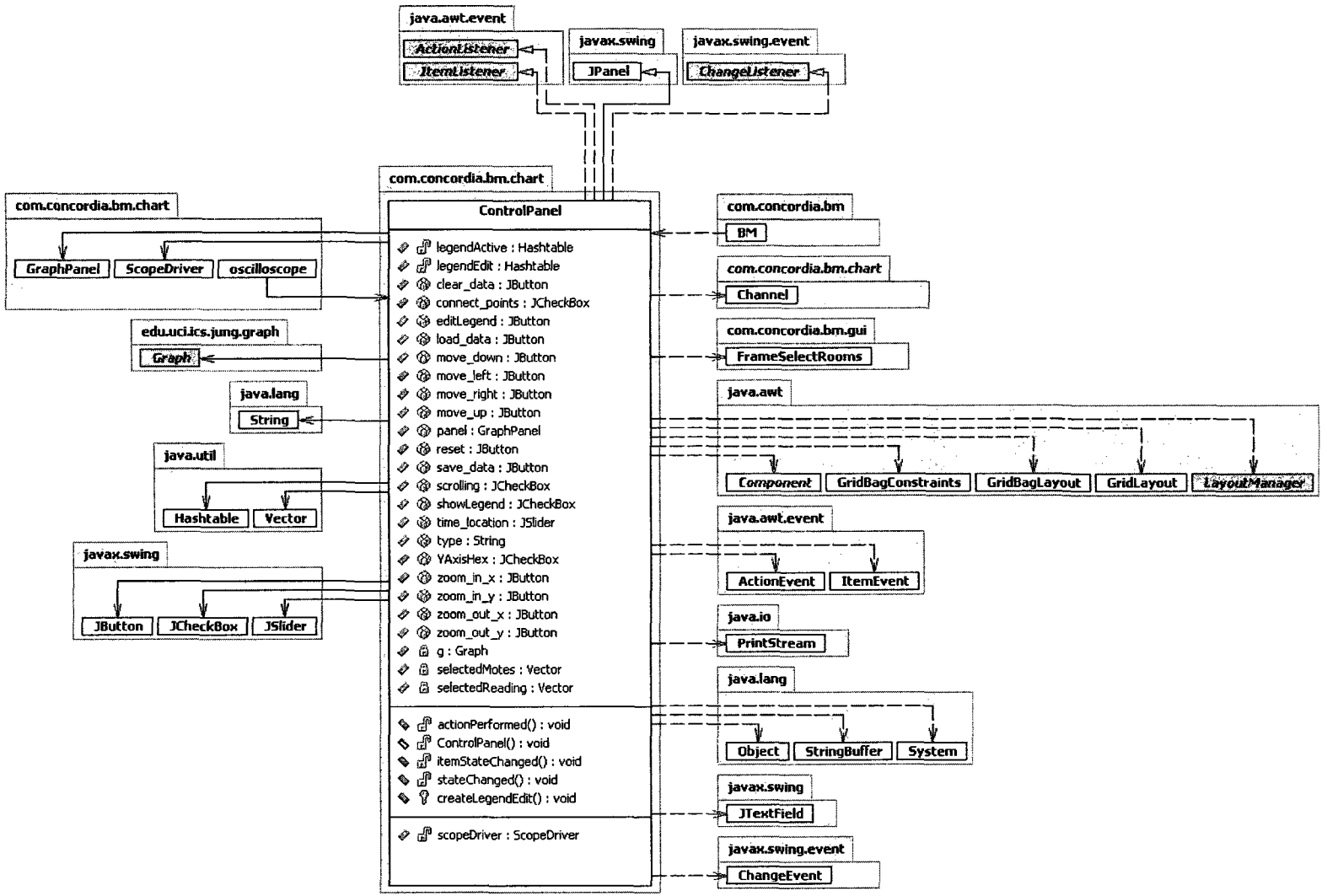


Figure 60: Class com.concordia.bm.chart.ControlPanel

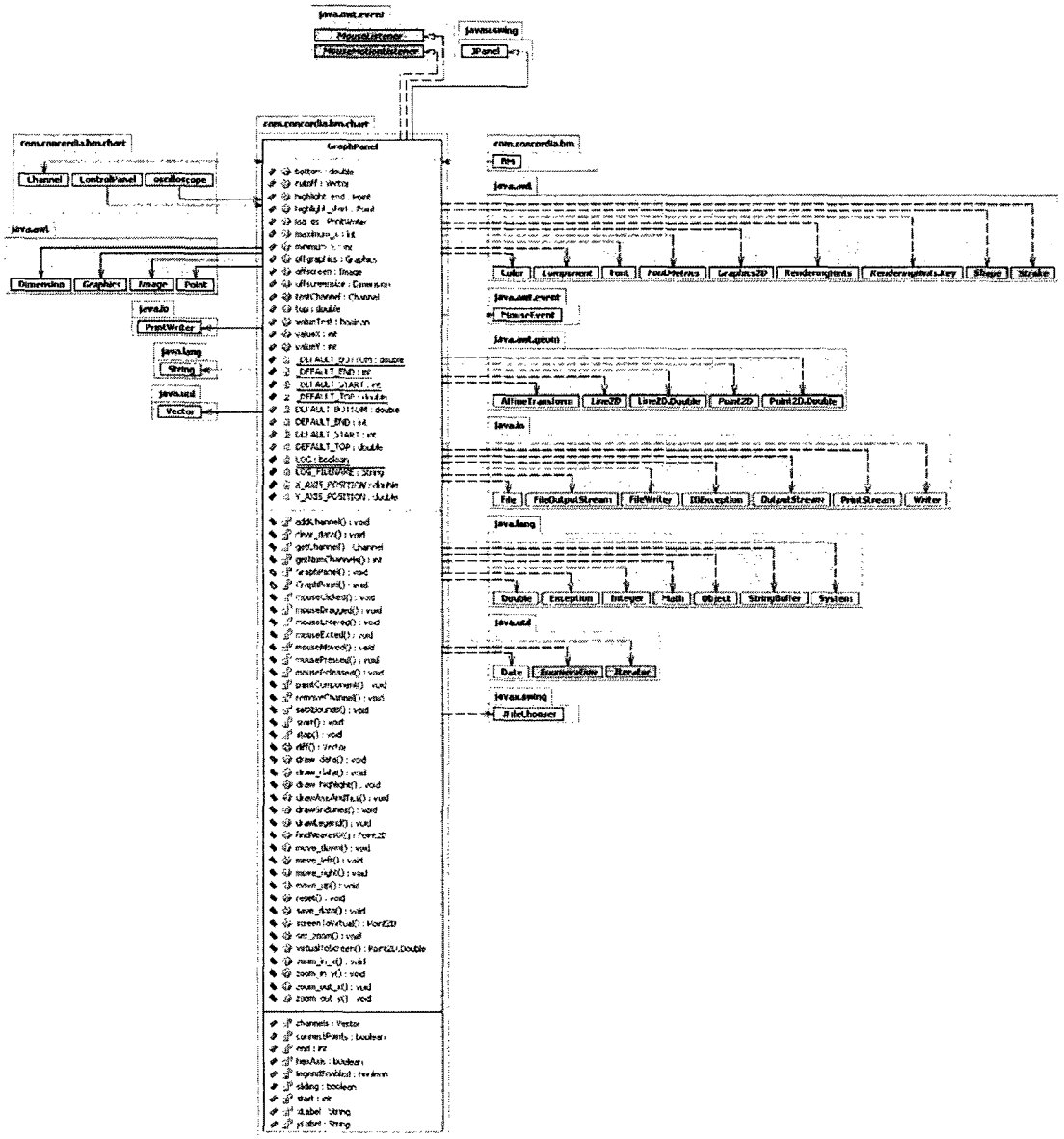


Figure 61: Class com.concordia.bm.chart.GraphPanel

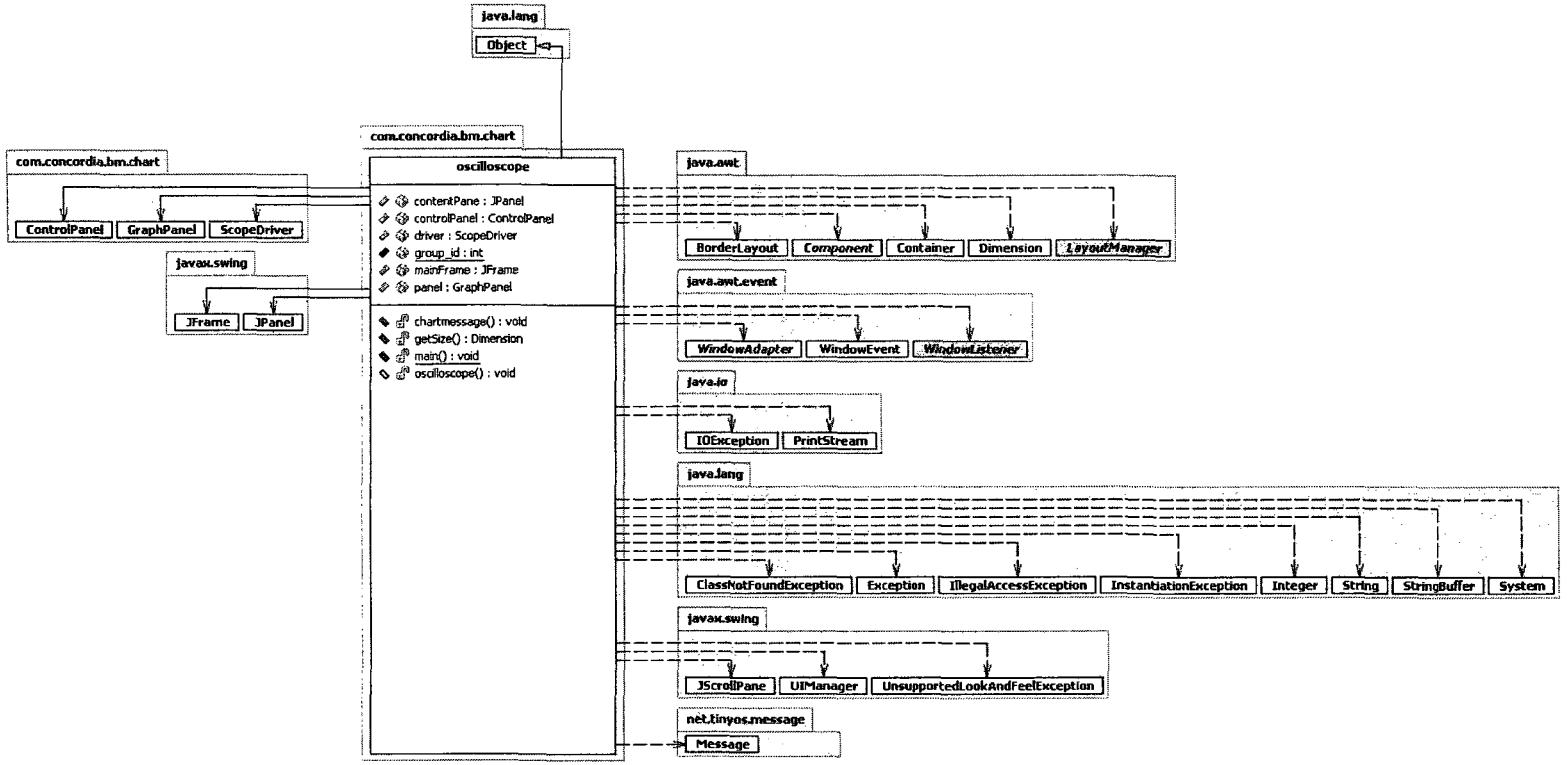


Figure 62: Class com.concordia.bm.chart.Oscilloscope

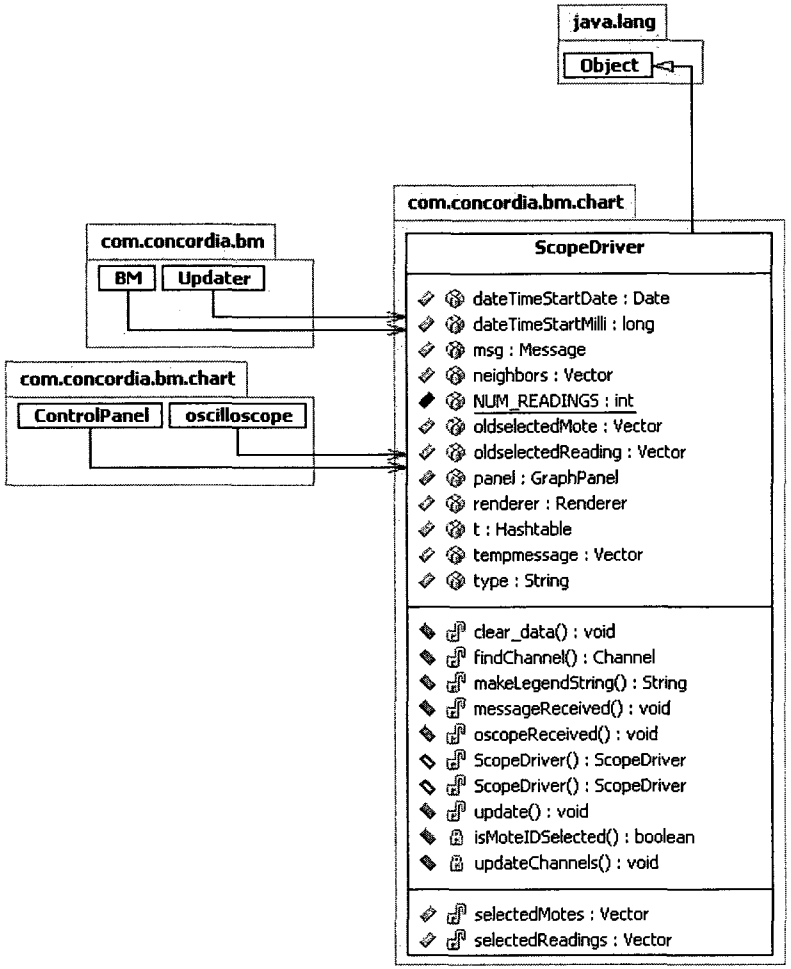


Figure 63: Class com.concordia.bm.chart.ScopeDriver

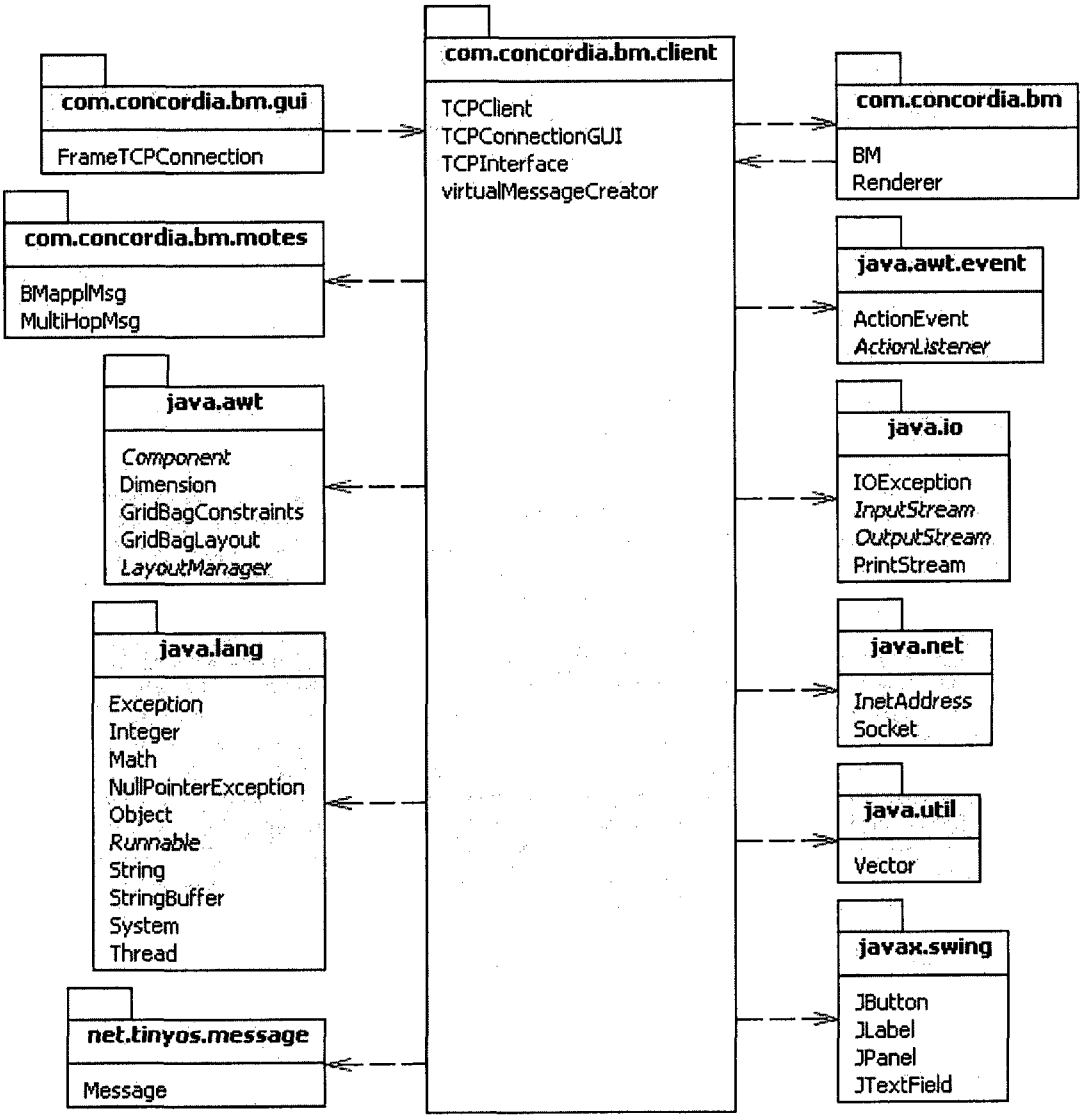


Figure 64: Package com.concordia.bm.client

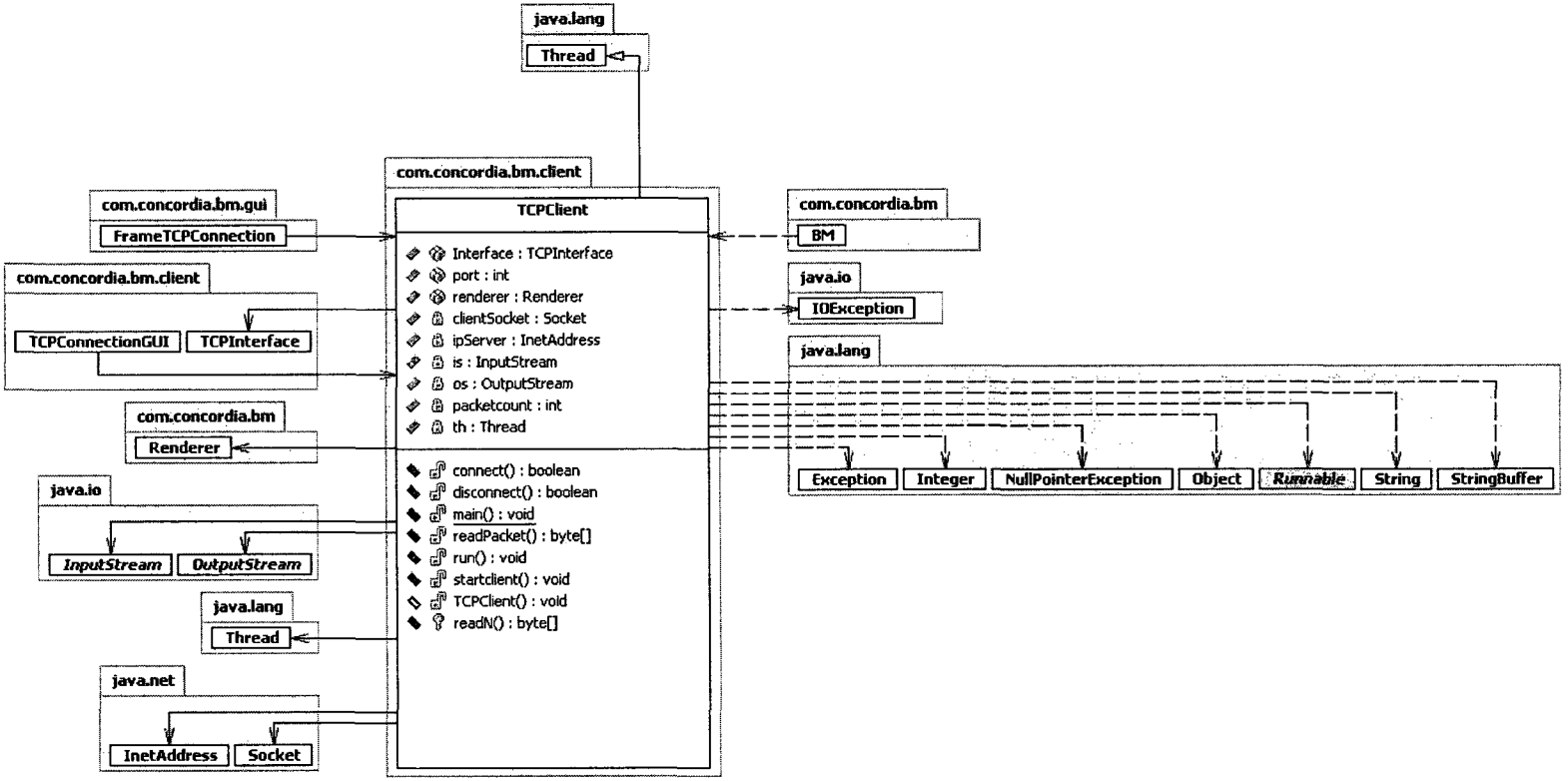


Figure 65: Class com.concordia.bm.client.TCPClient

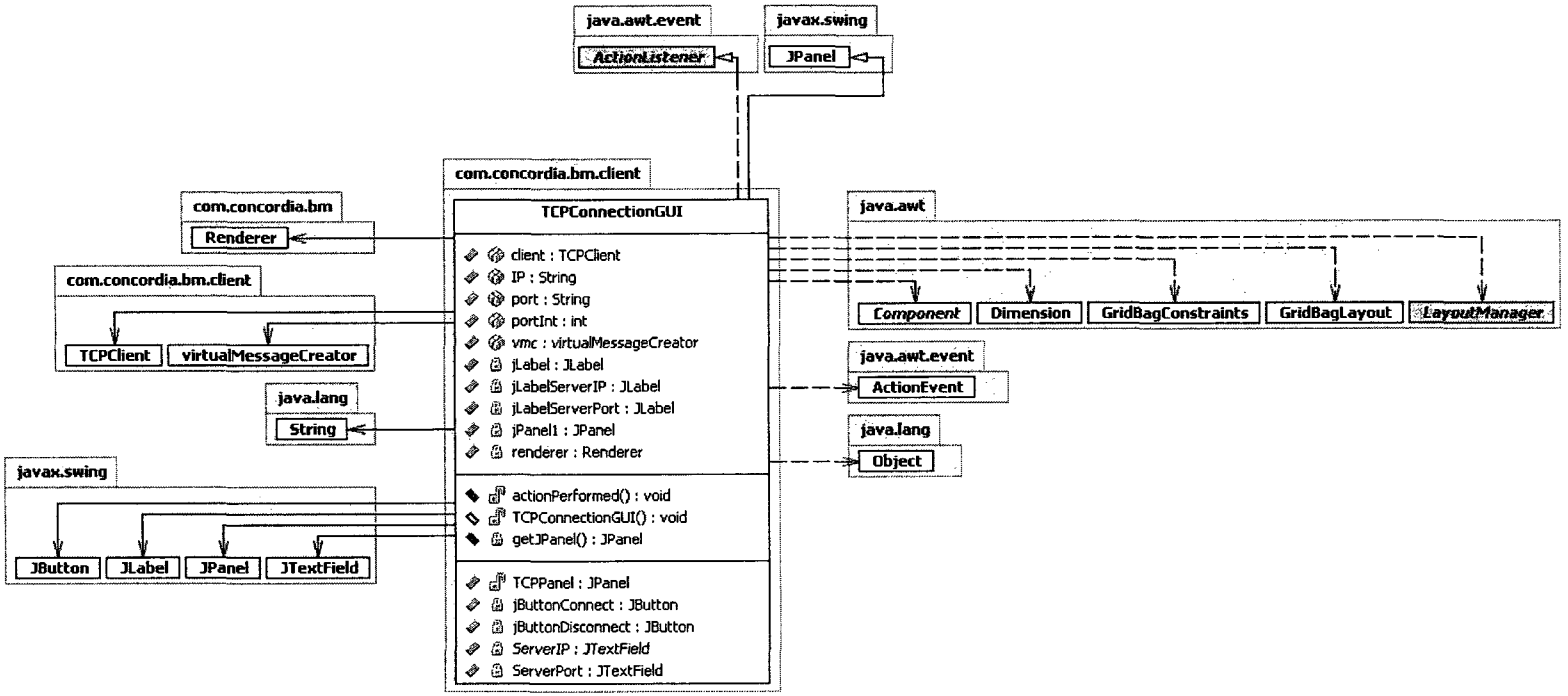


Figure 66: Class com.concordia.bm.client.TCPConnectionGUI

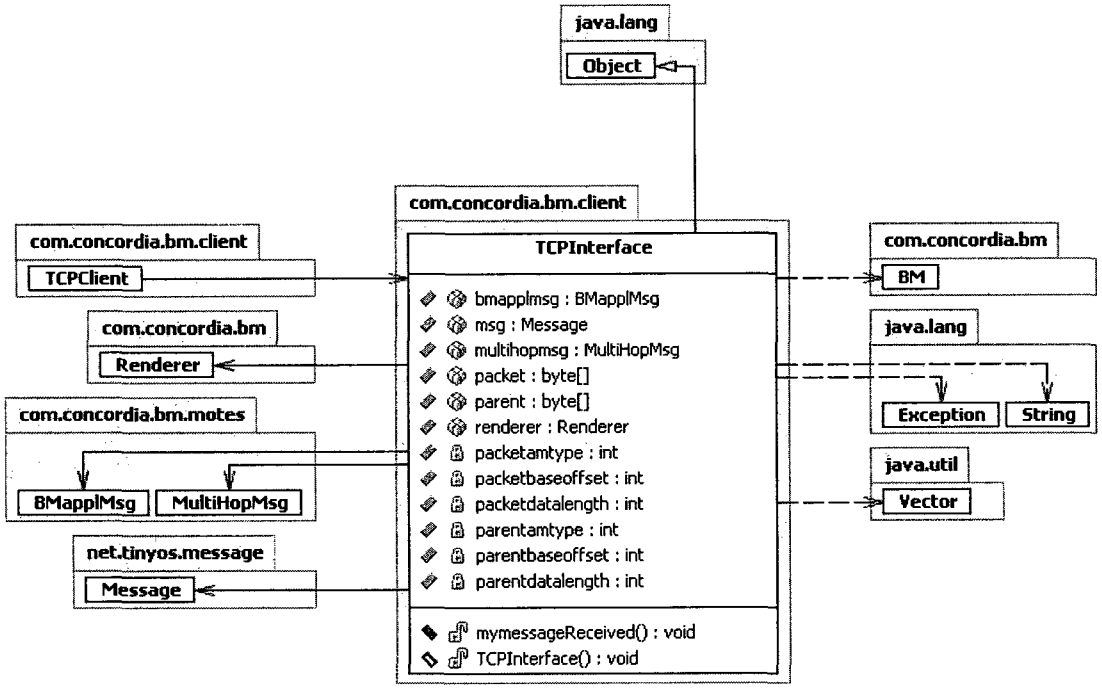


Figure 67: Class com.concordia.bm.client.TCPInterface

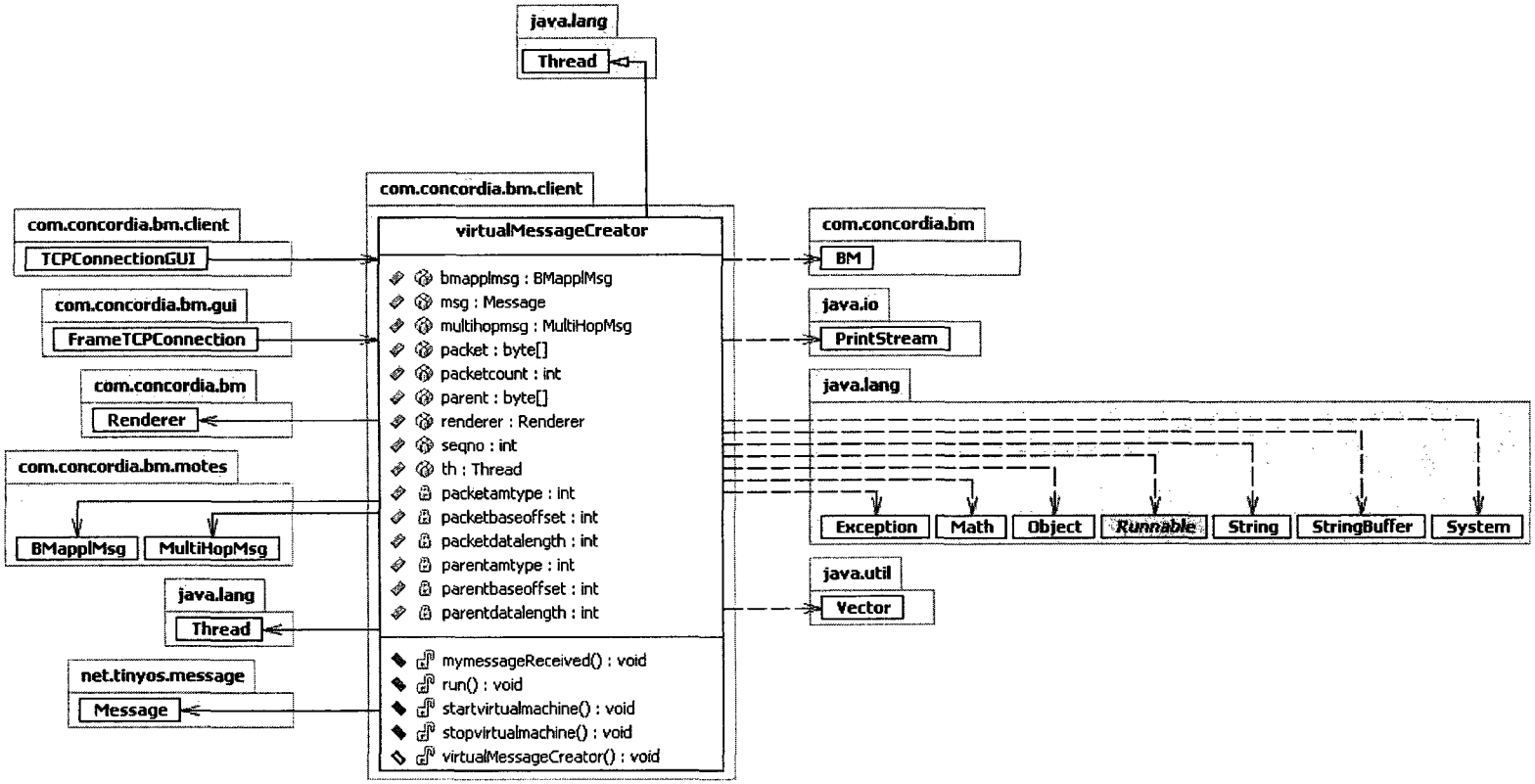


Figure 68: Class com.concordia.bm.client.VirtualMessageCreator

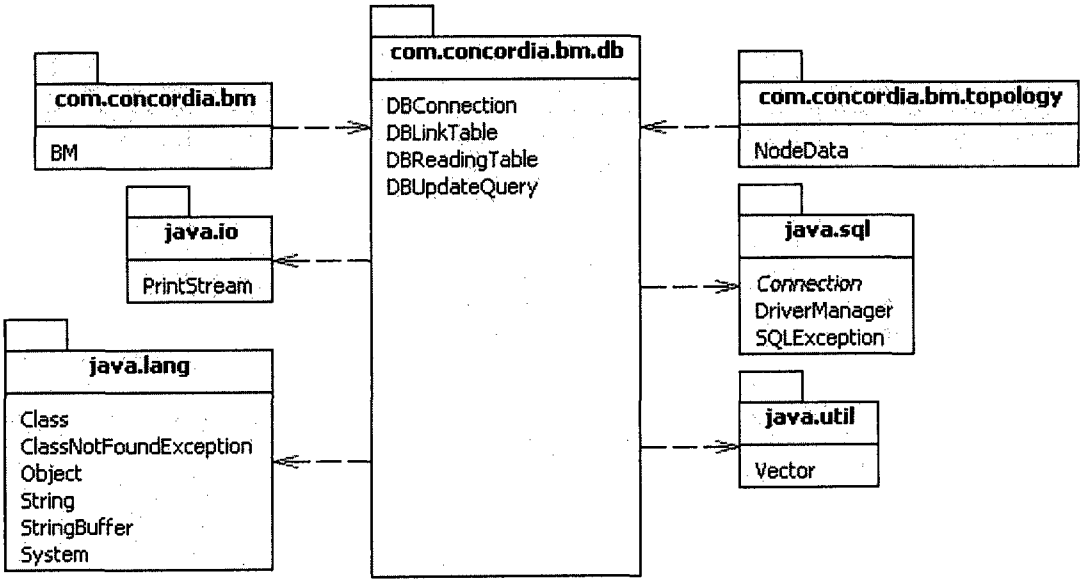


Figure 69: Package com.concordia.bm.db

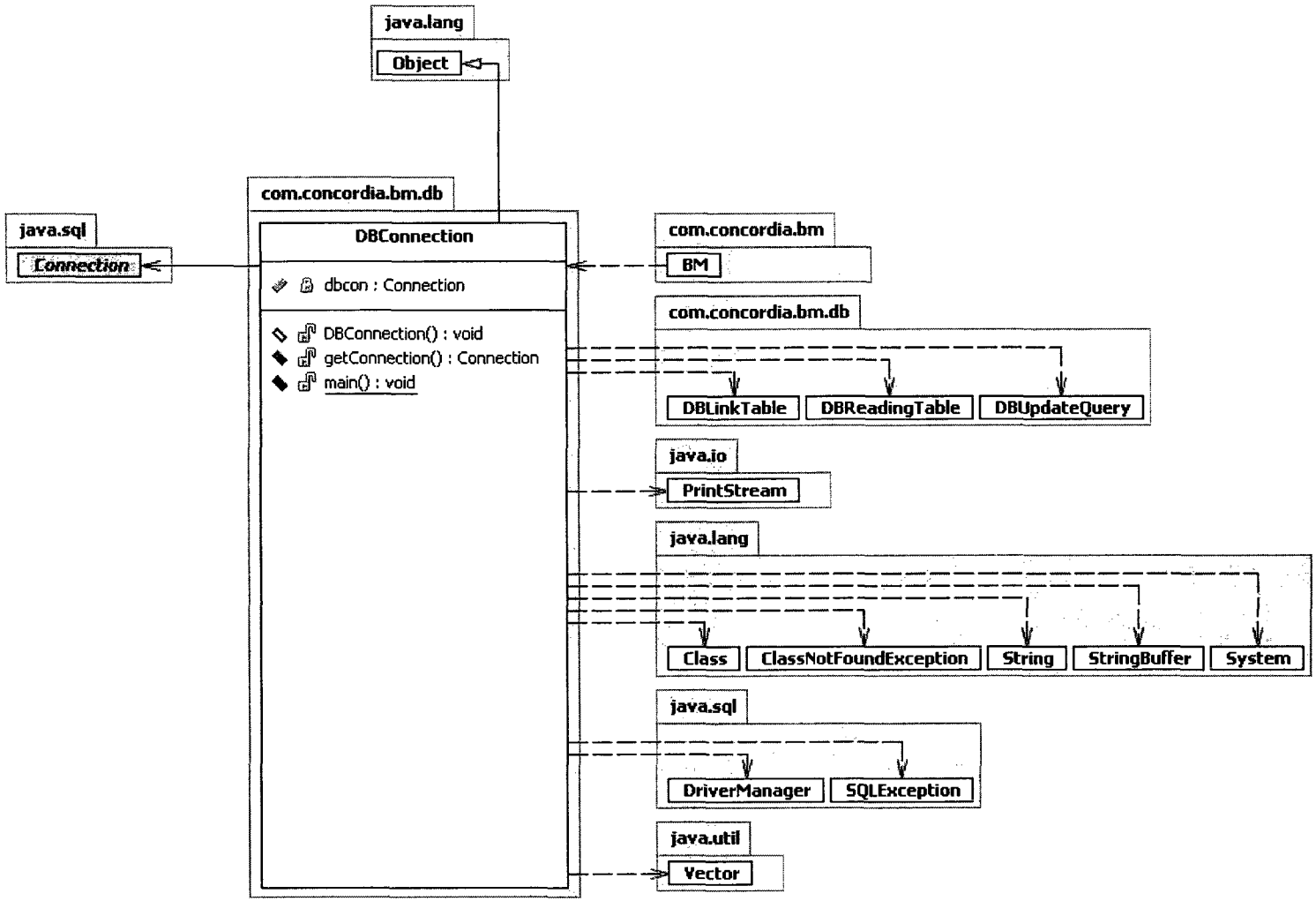


Figure 70: Class com.concordia.bm.db.DBConnection

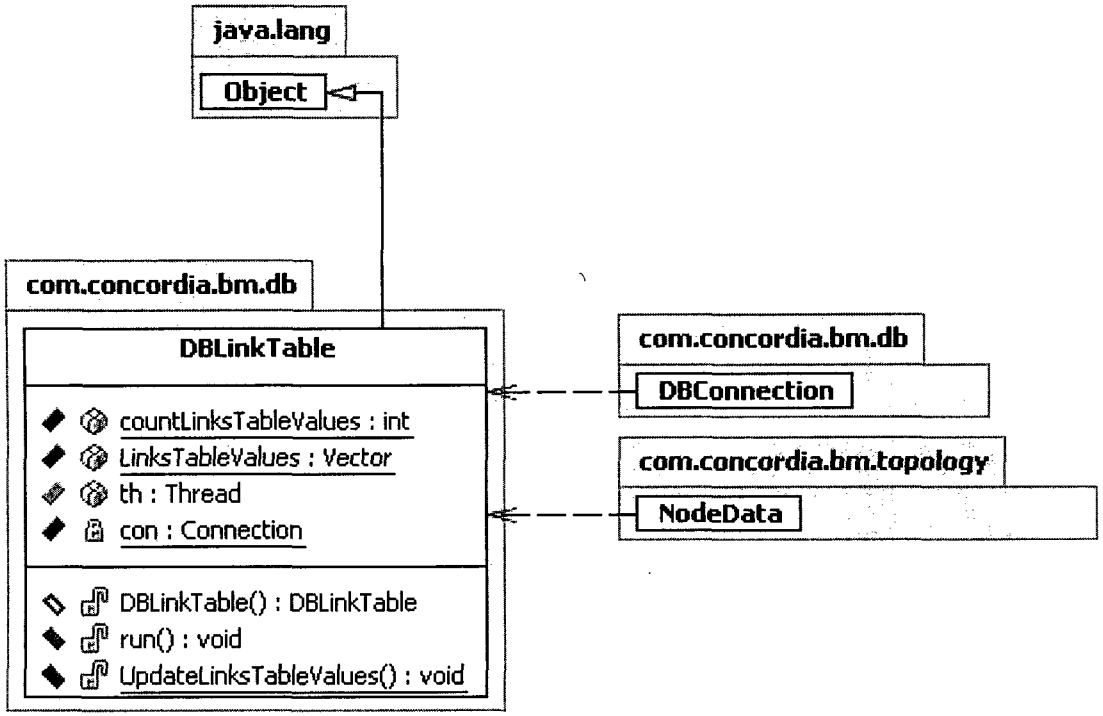


Figure 71: Class com.concordia.bm.db.DBLinkTable

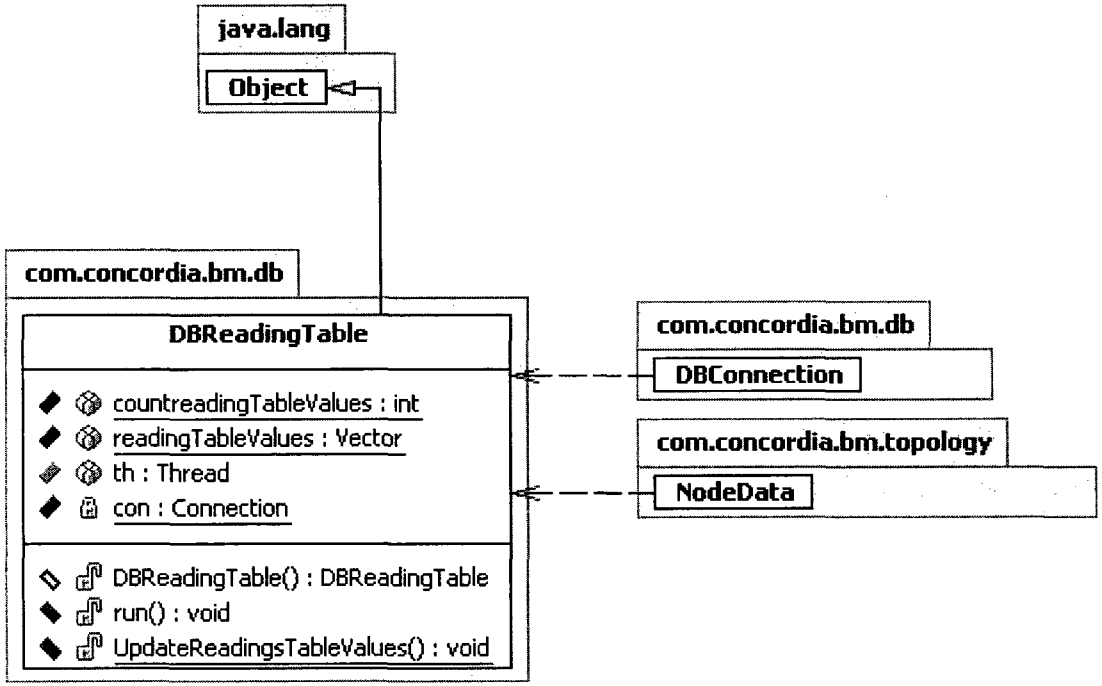


Figure 72: Class com.concordia.bm.db.DBReadingTable

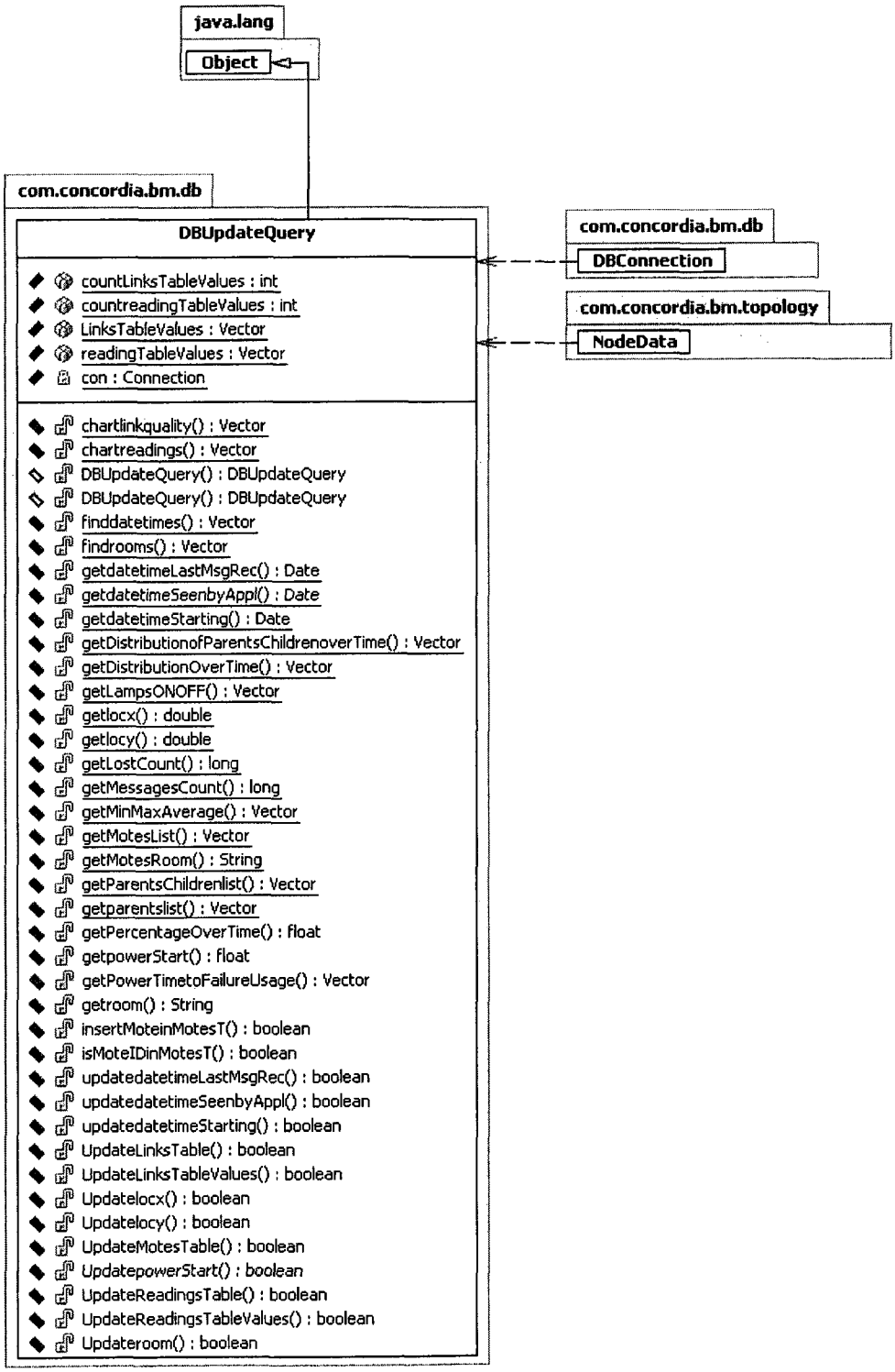


Figure 73: Class com.concordia.bm.db.DBUpdateQuery

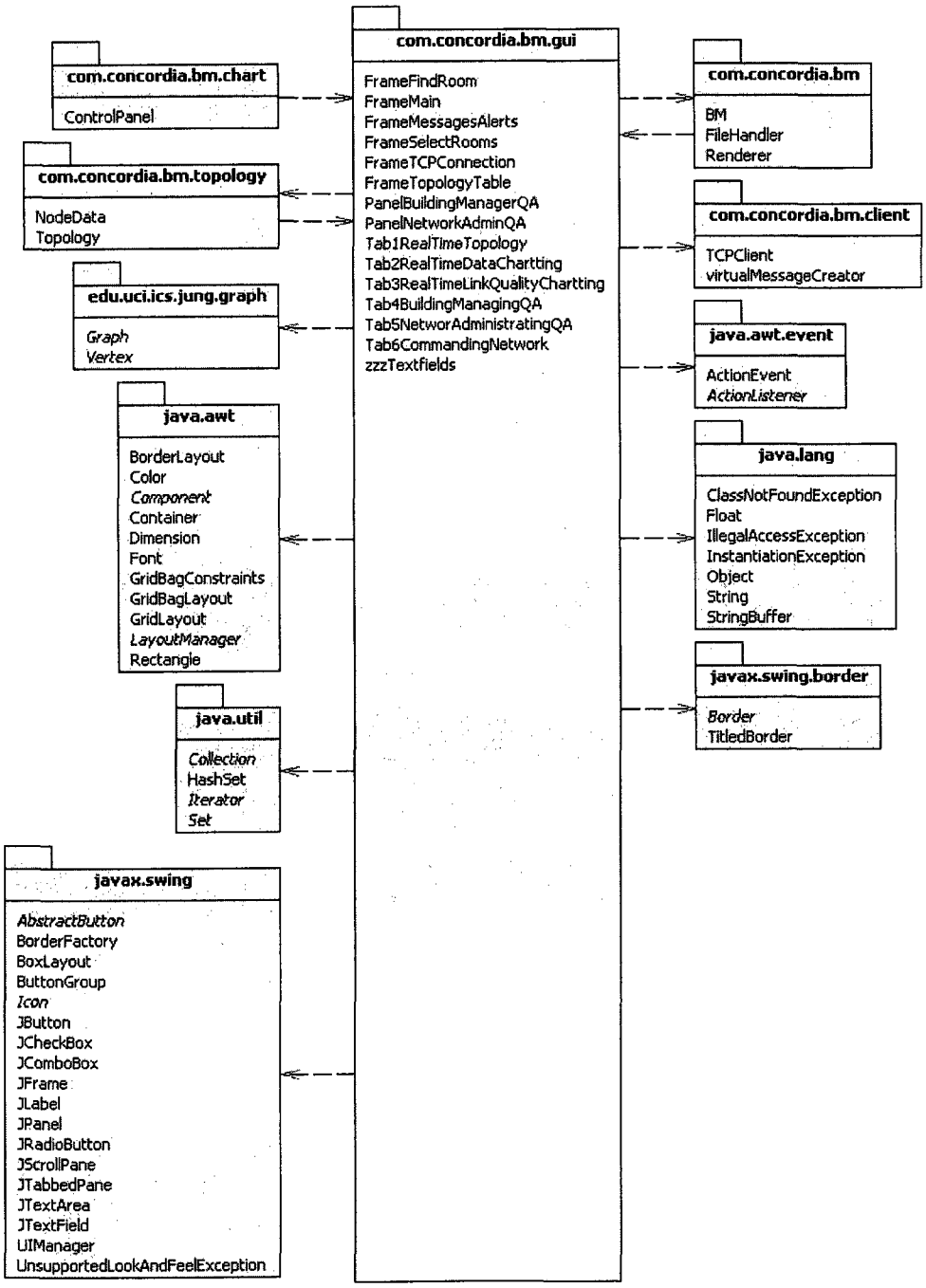


Figure 74: Package com.concordia.bm.gui

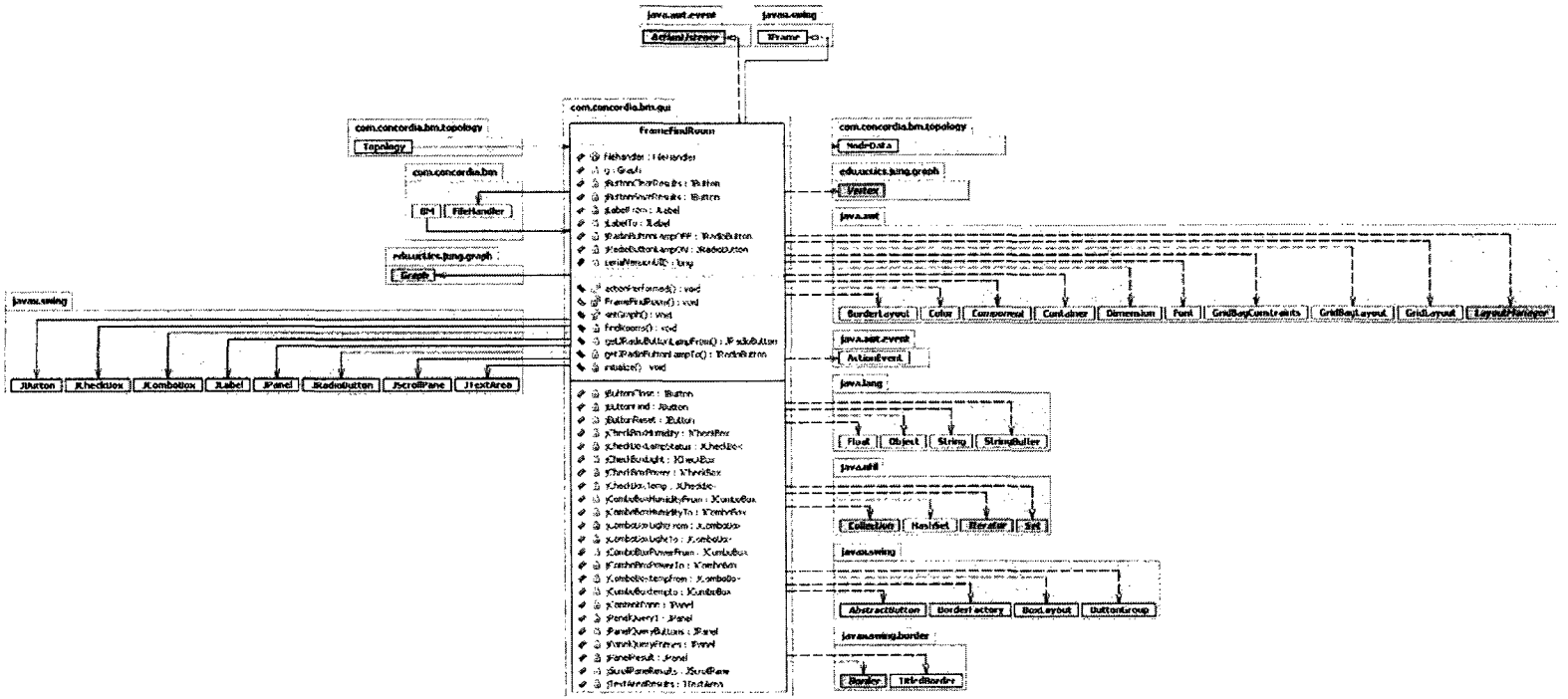


Figure 75: Class com.concordia.bm.gui.FrameFindRoom

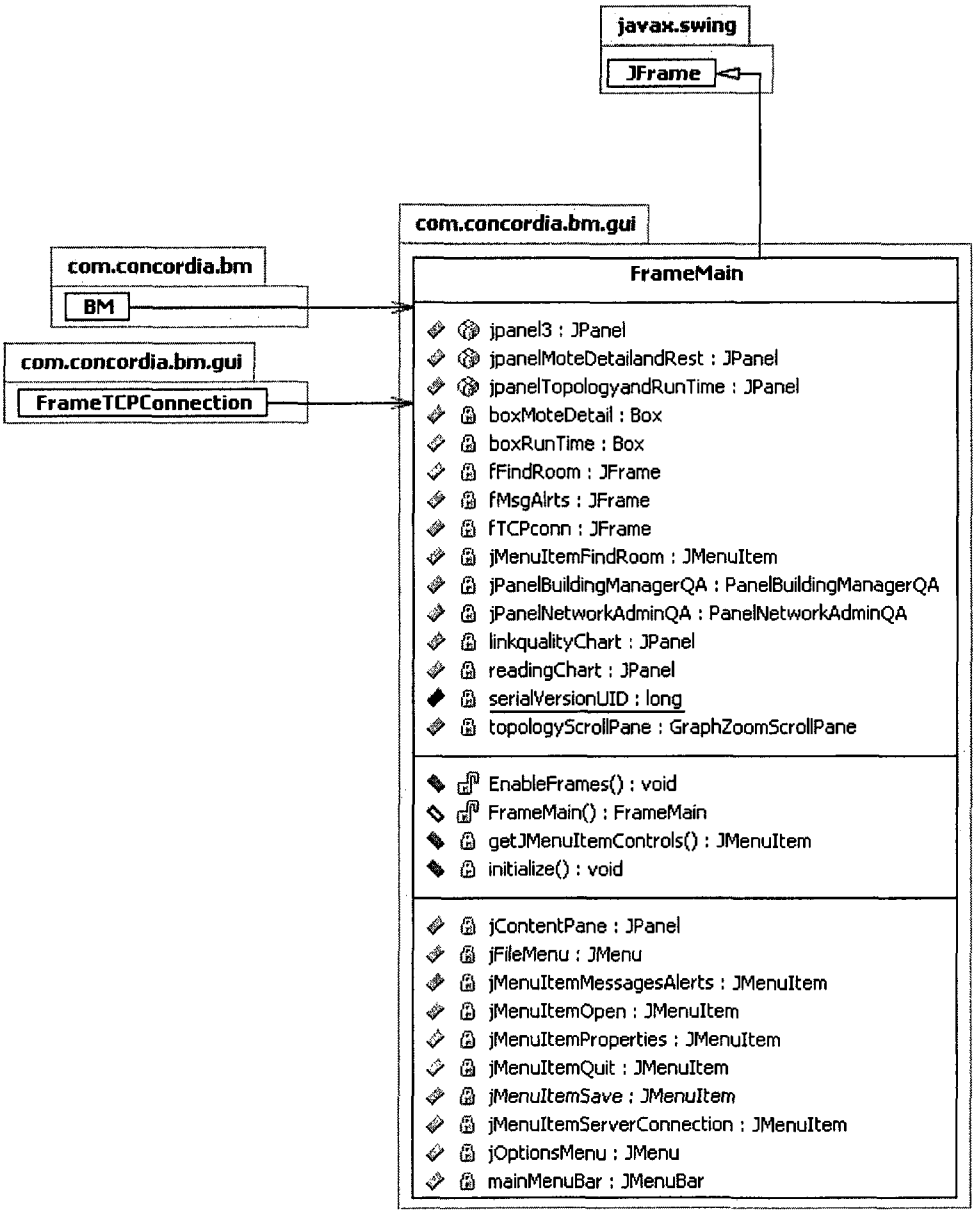


Figure 76: Class com.concordia.bm.gui.FrameMain

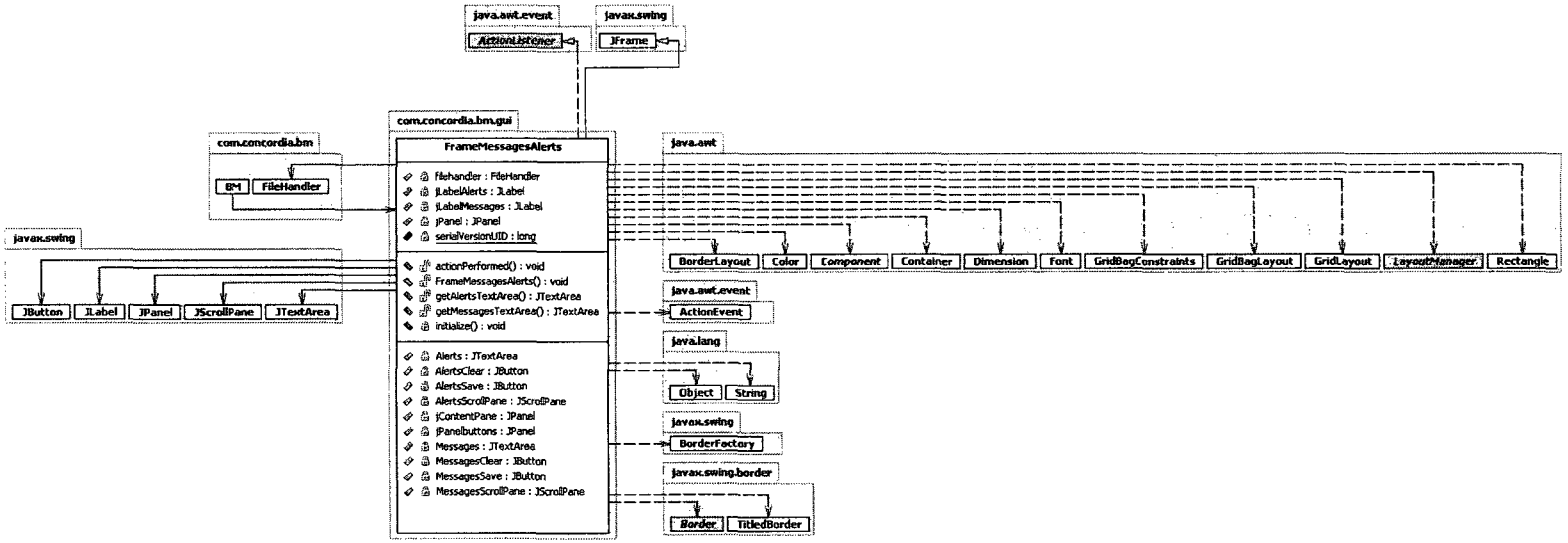


Figure 77: Class com.concordia.bm.gui.FrameMessagesAlerts

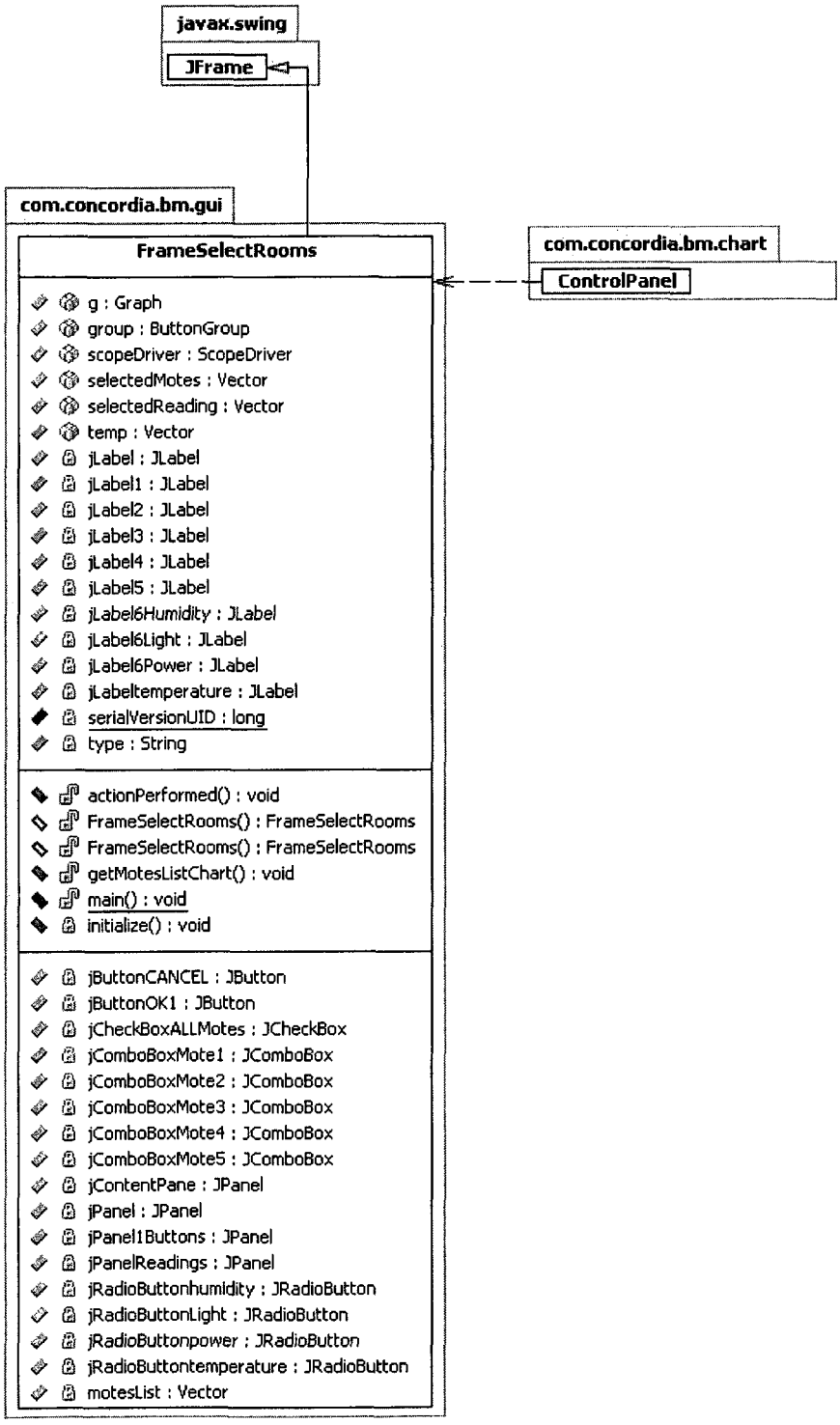


Figure 78: Class com.concordia.bm.gui.FrameSelectRooms

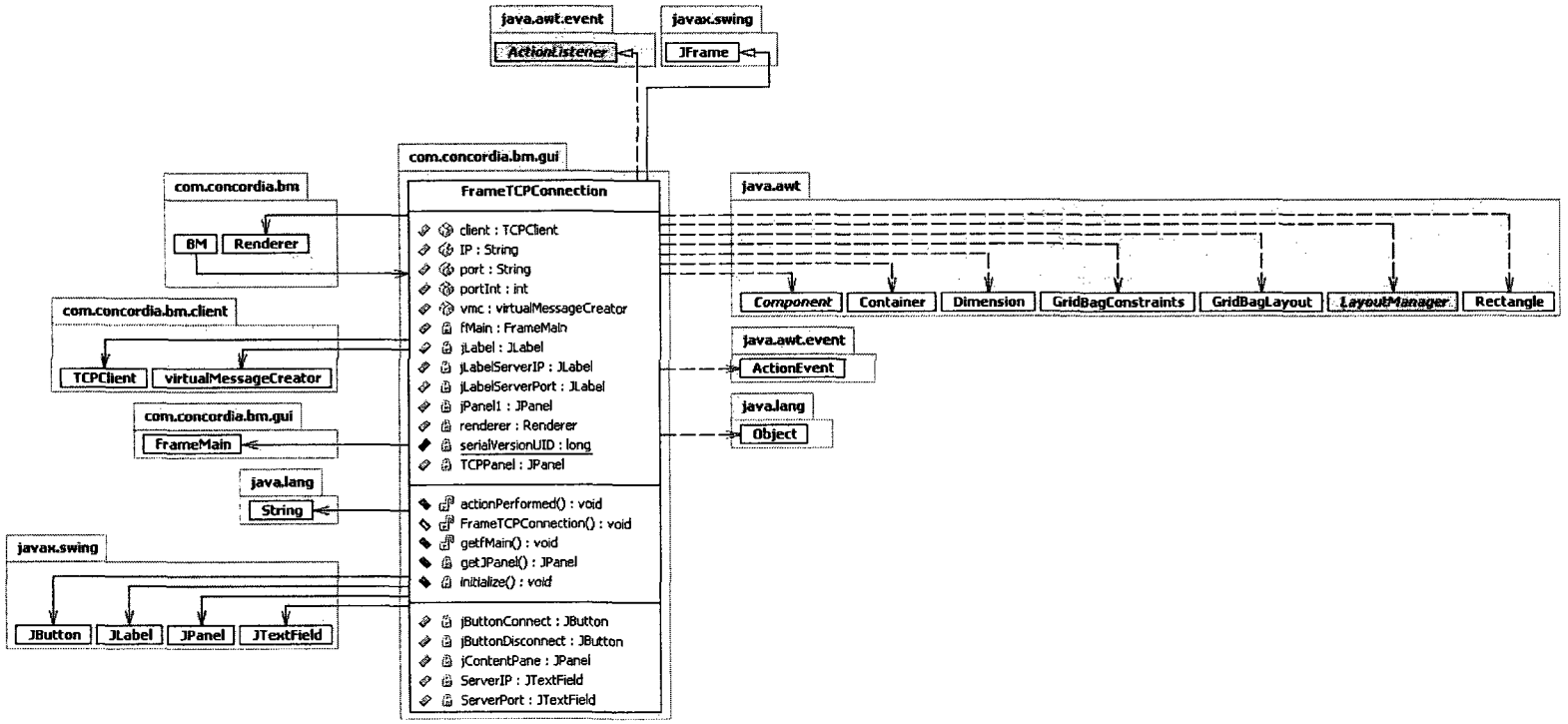


Figure 79: Class com.concordia.bm.gui.FrameTCPConnection

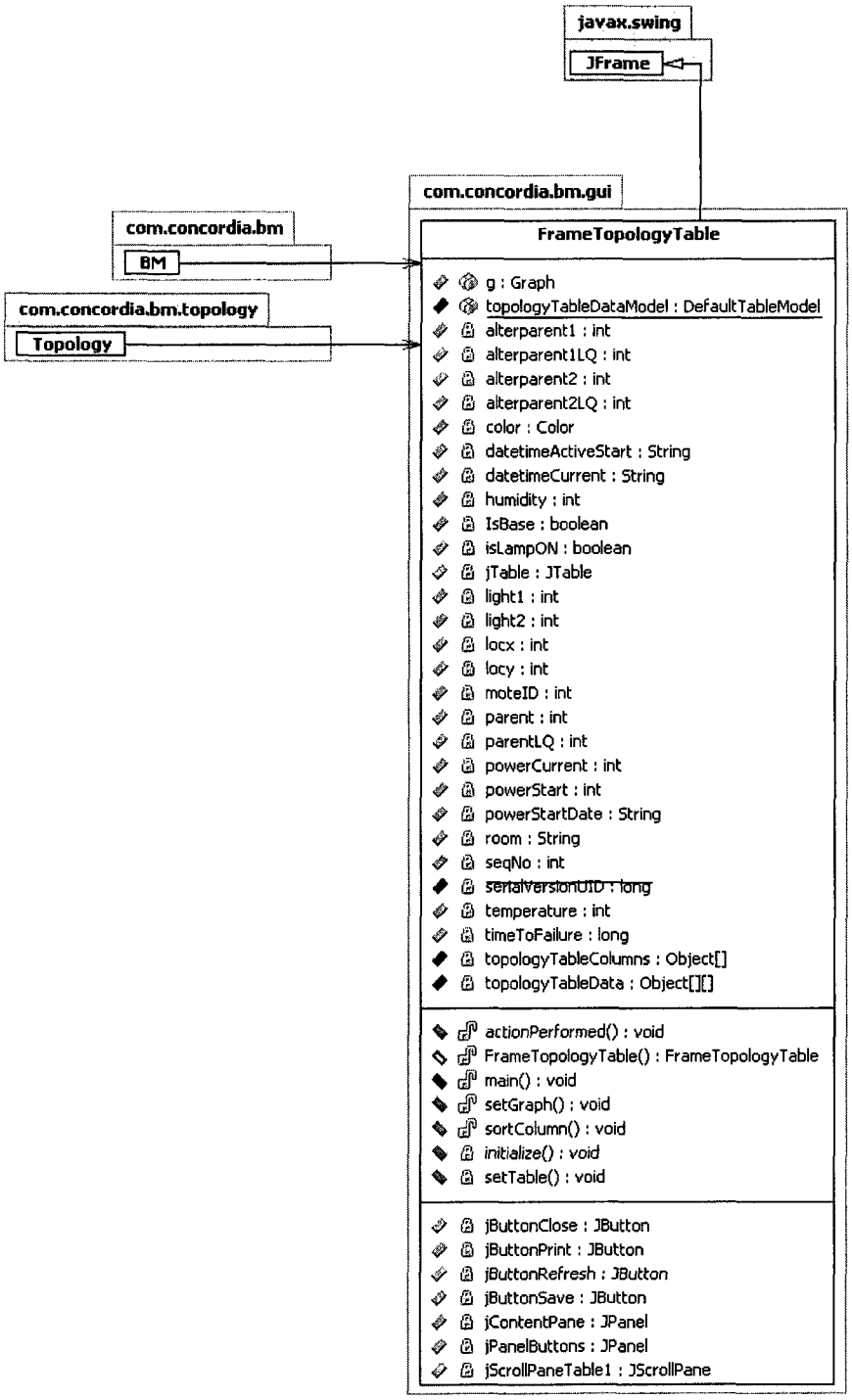


Figure 80: Class com.concordia.bm.gui.FrameTopologyTable

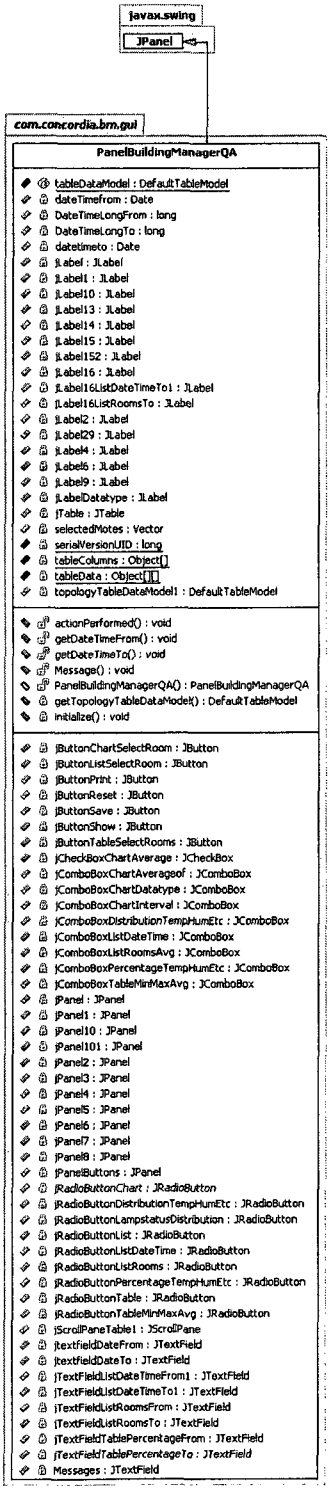


Figure 81: Class com.concordia.bm.gui.PanelBuildingManagerQ

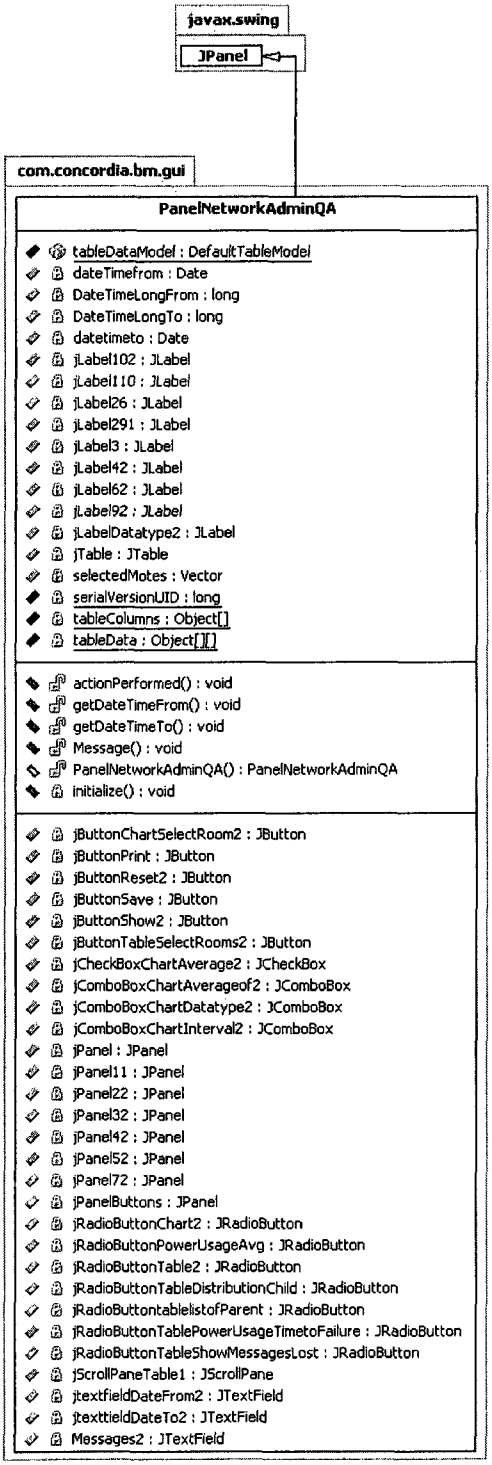


Figure 82: Class com.concordia.bm.gui.PanelNetworkAdminQA

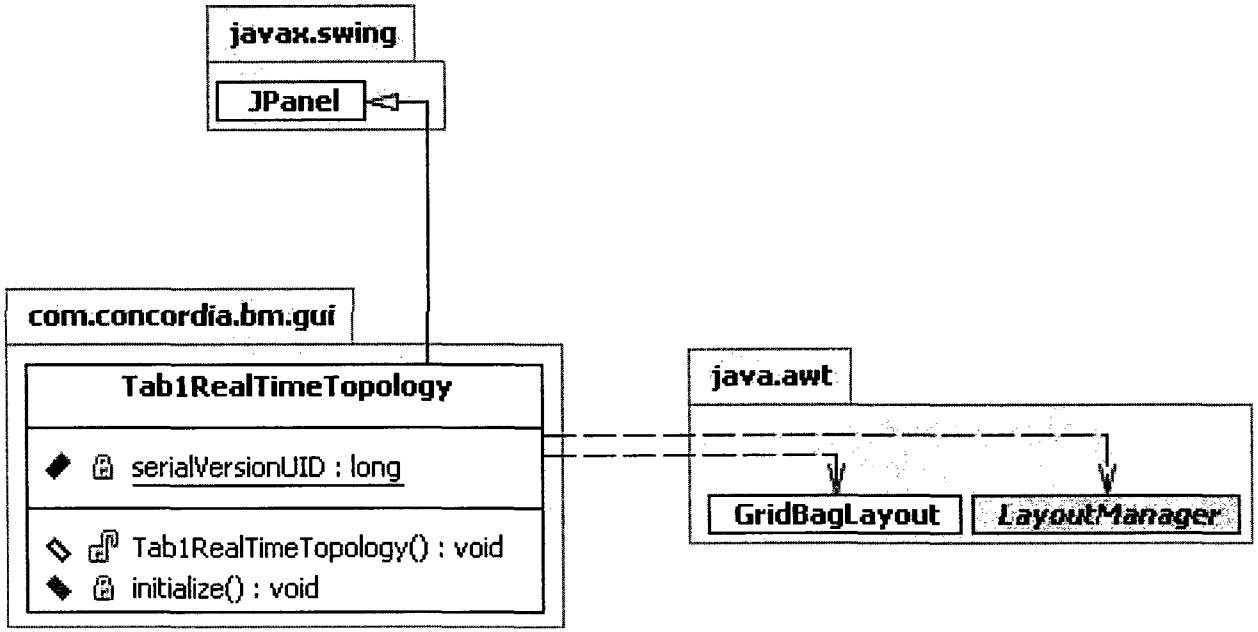


Figure 83: Class com.concordia.bm.gui.Tab1RealTimeTopology

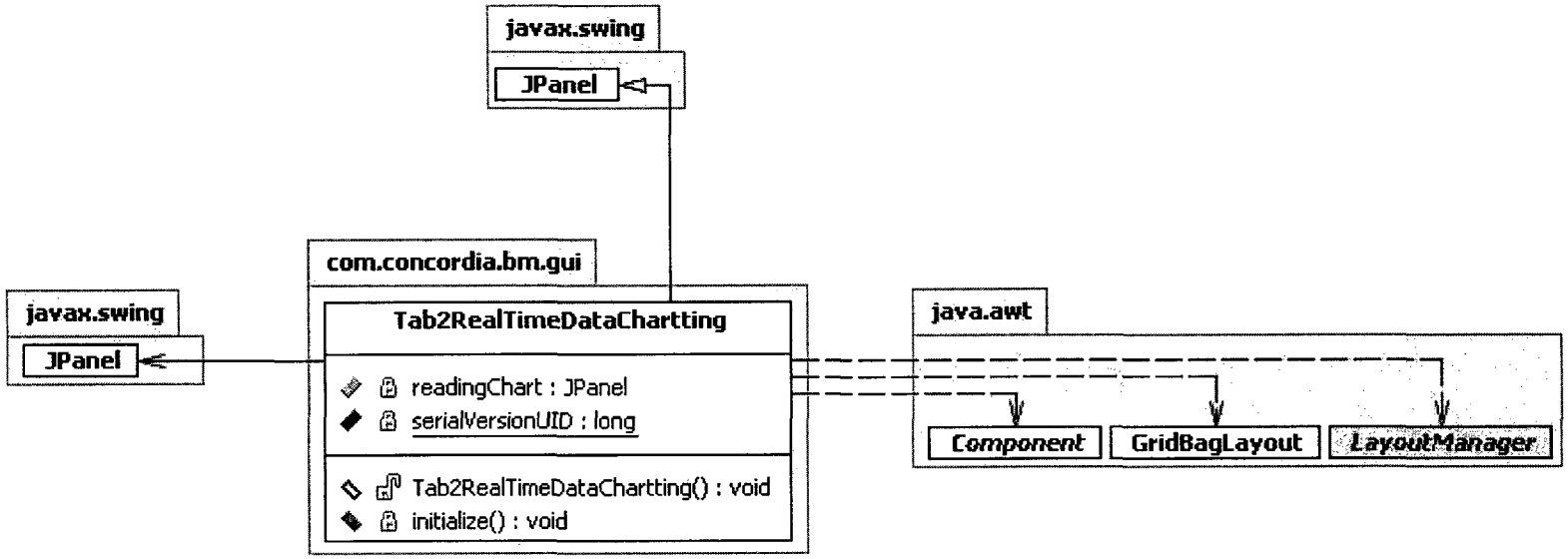


Figure 84: Class com.concordia.bm.gui.Tab2RealTimeDataChartting

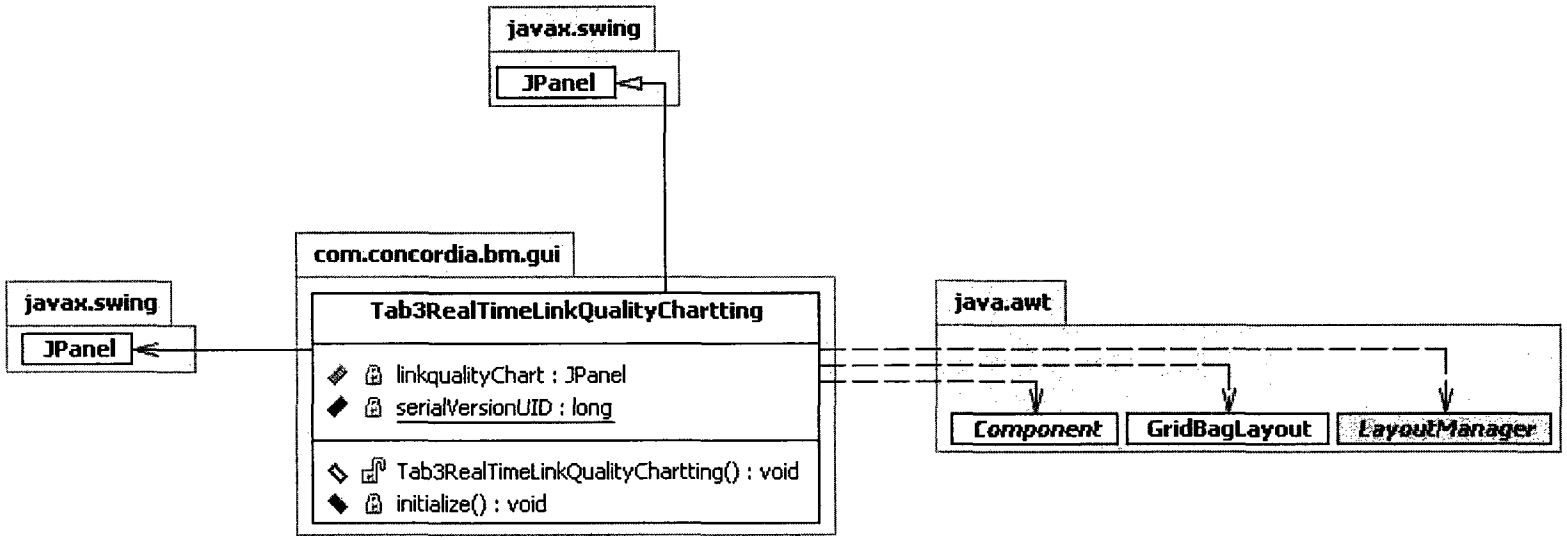


Figure 85: Class com.concordia.bm.gui.Tab3RealTimeLinkQualityChartting

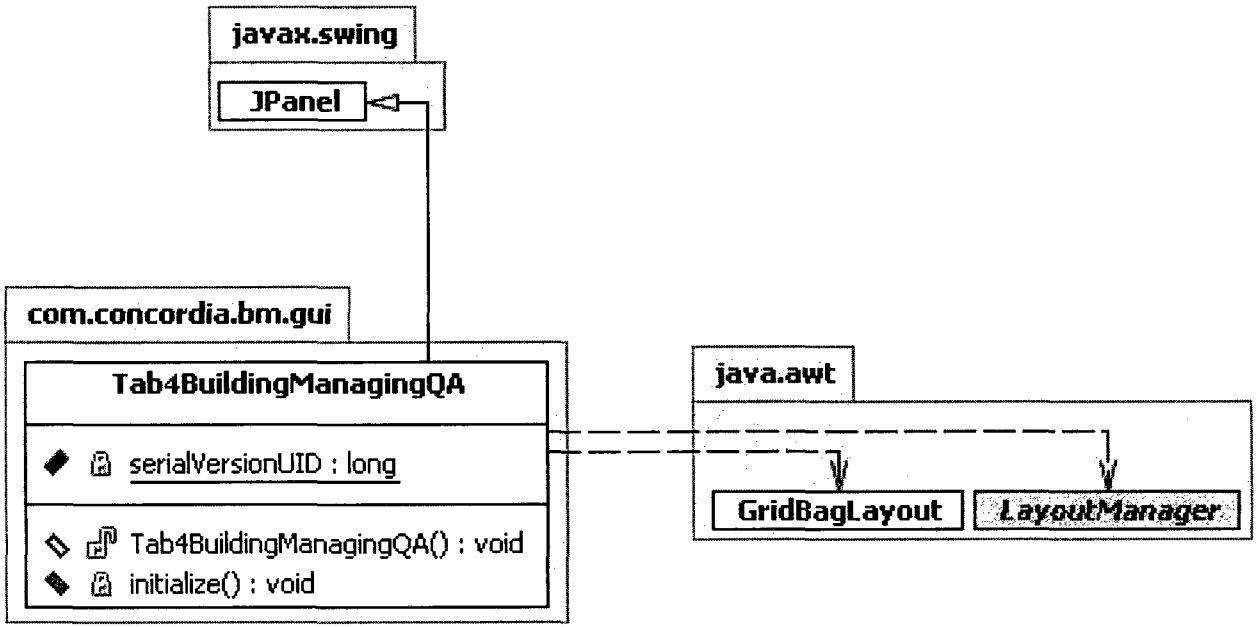


Figure 86: Class com.concordia.bm.gui.Tab4BuildingManagingQA

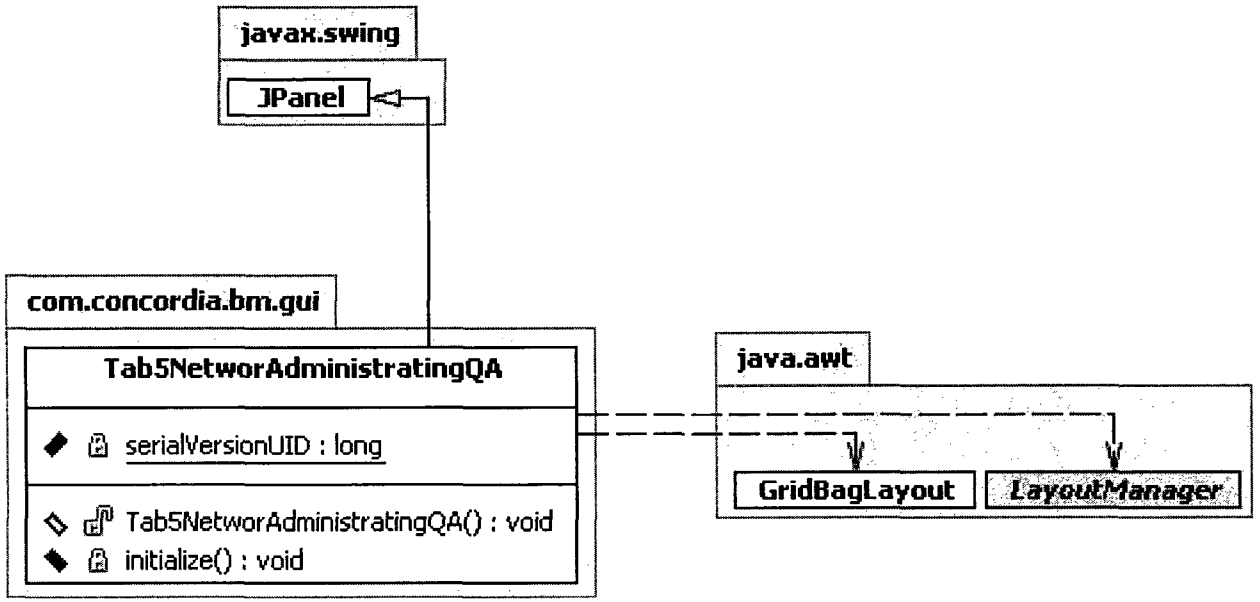


Figure 87: Class com.concordia.bm.gui.Tab5NetworAdministratingQA

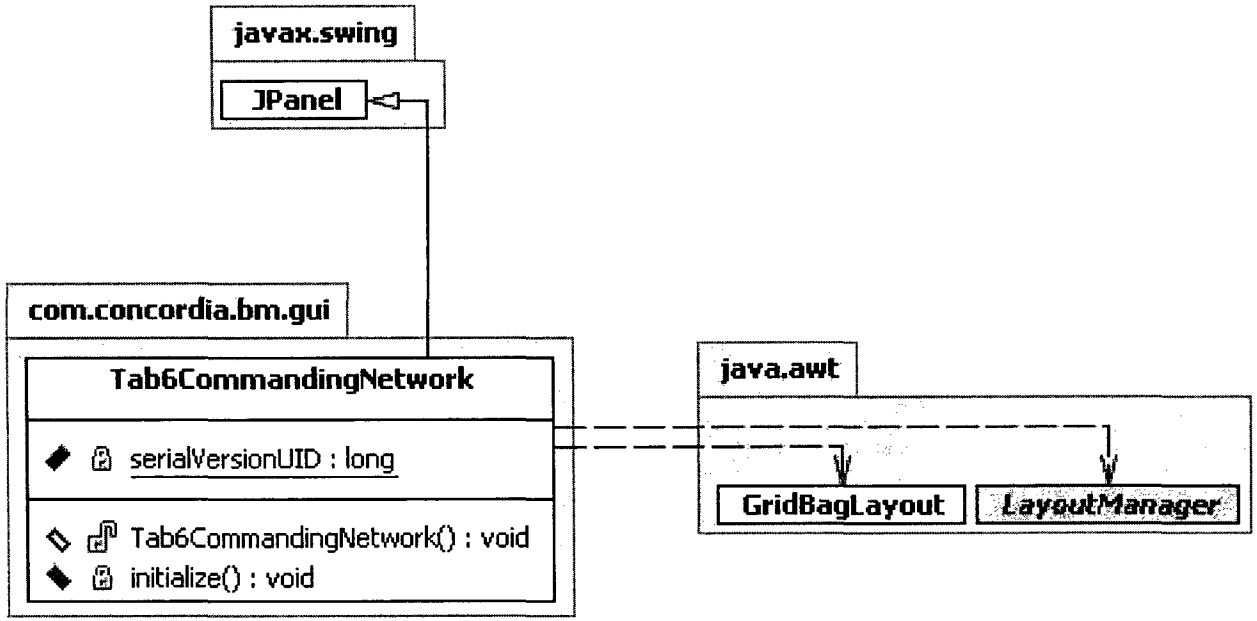


Figure 88: Class com.concordia.bm.gui.Tab6CommandingNetwork

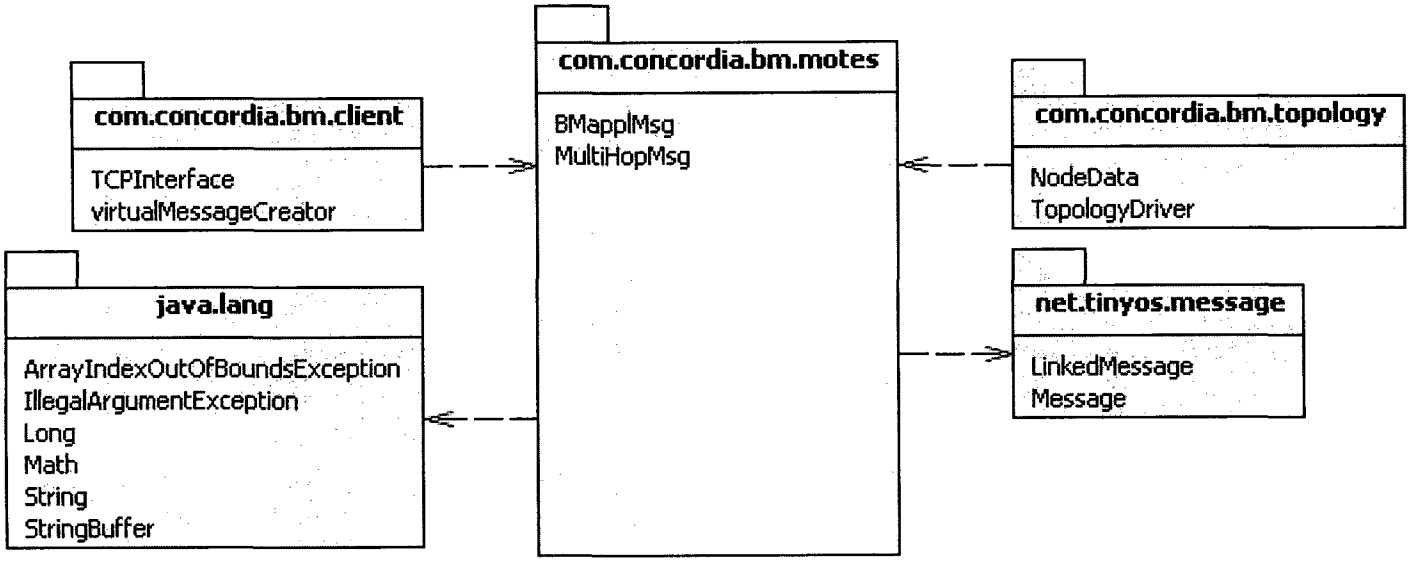


Figure 89: Package com.concordia.bm.motes

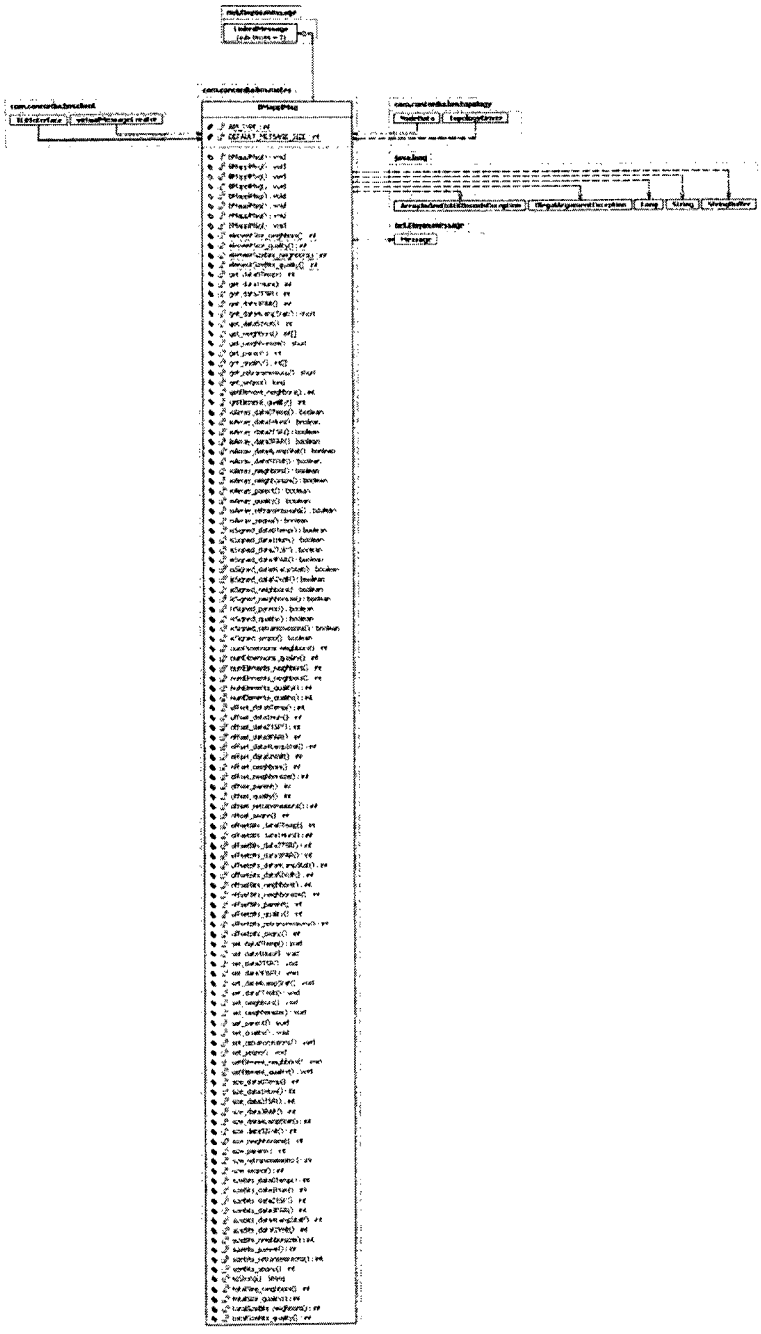


Figure 90: Class com.concordia.bm.motes.BMapplMsg

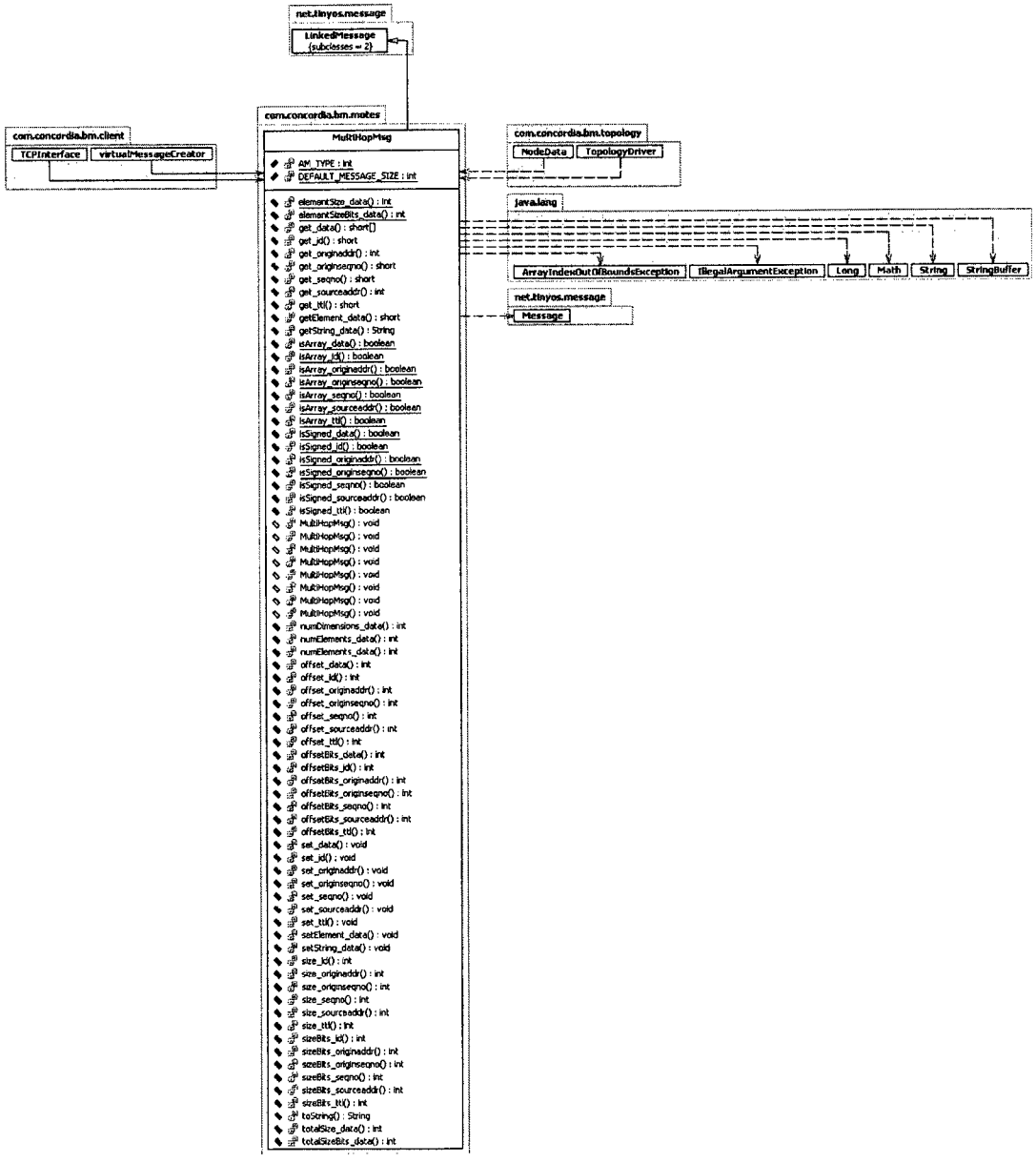


Figure 91: Class com.concordia.bm.motes.MultiHopMsg

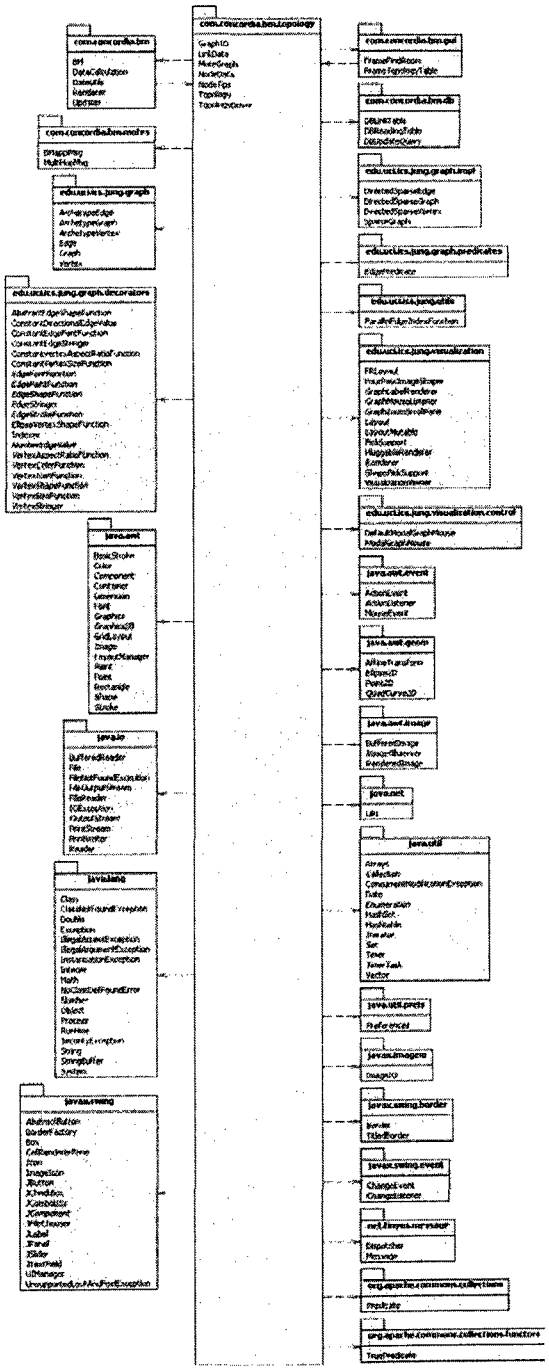


Figure 92: Package com.concordia.bm.topology

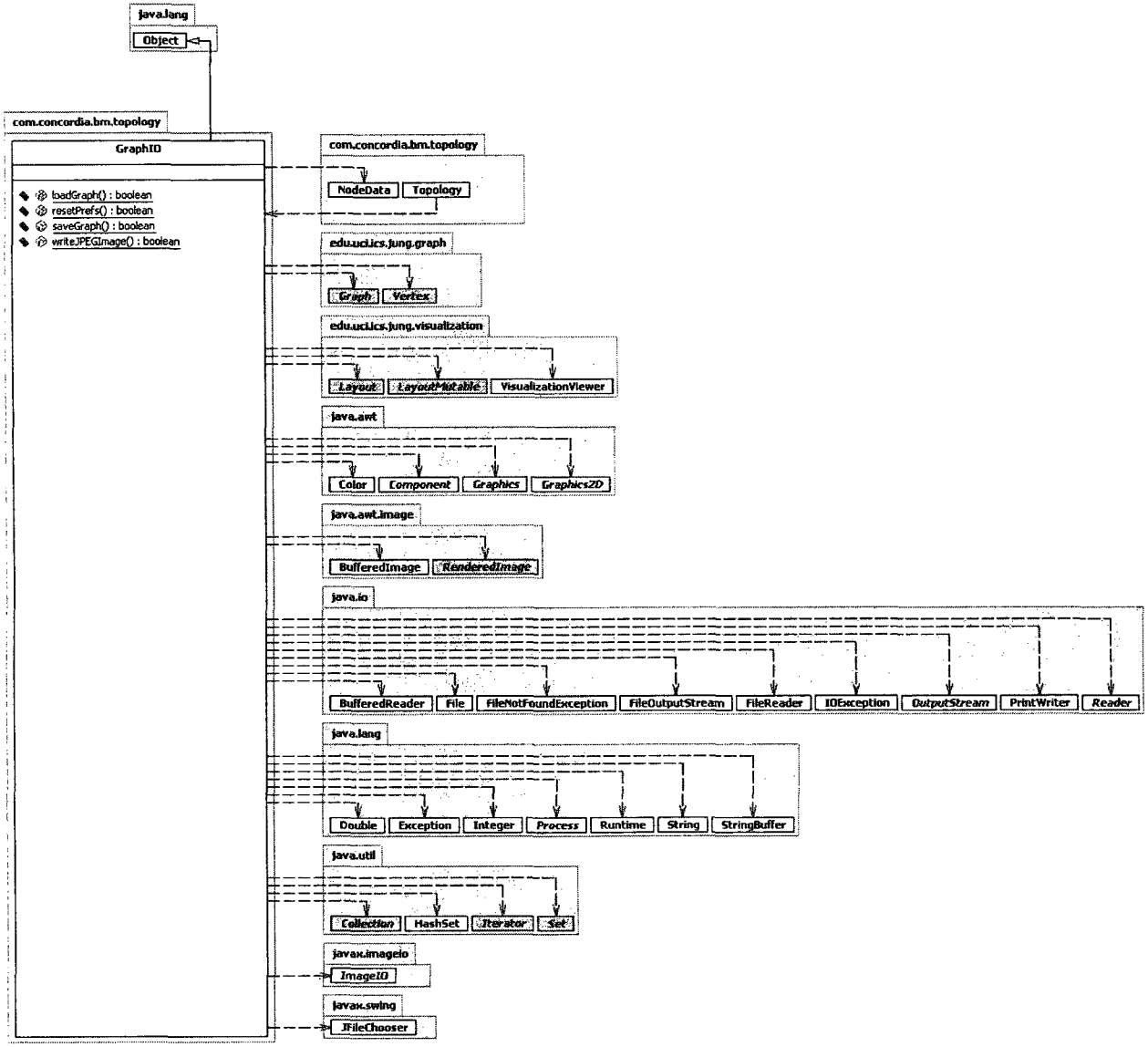


Figure 93: Class com.concordia.bm.topology.GraphIO

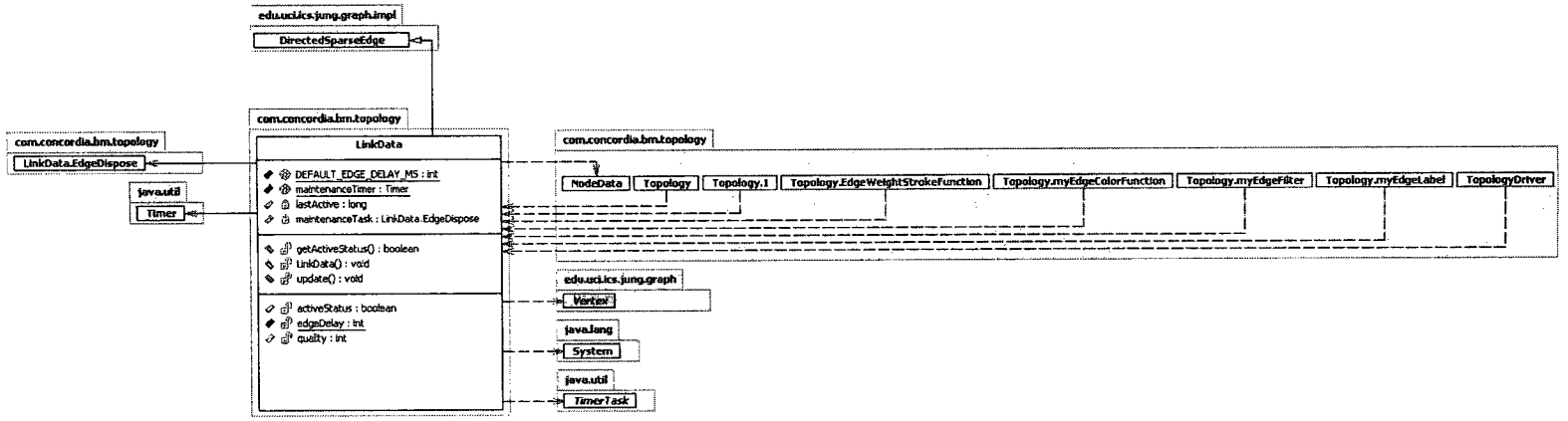


Figure 94: Class com.concordia.bm.topology.LinkData

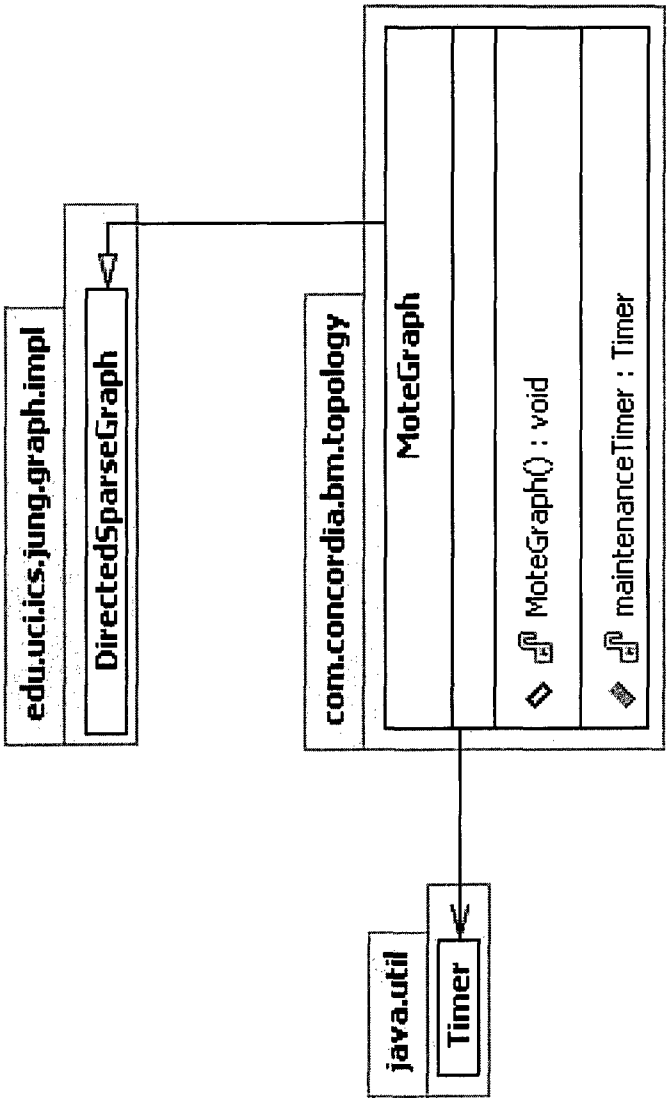


Figure 95: Class com.concordia.bm.topology.MoteGraph

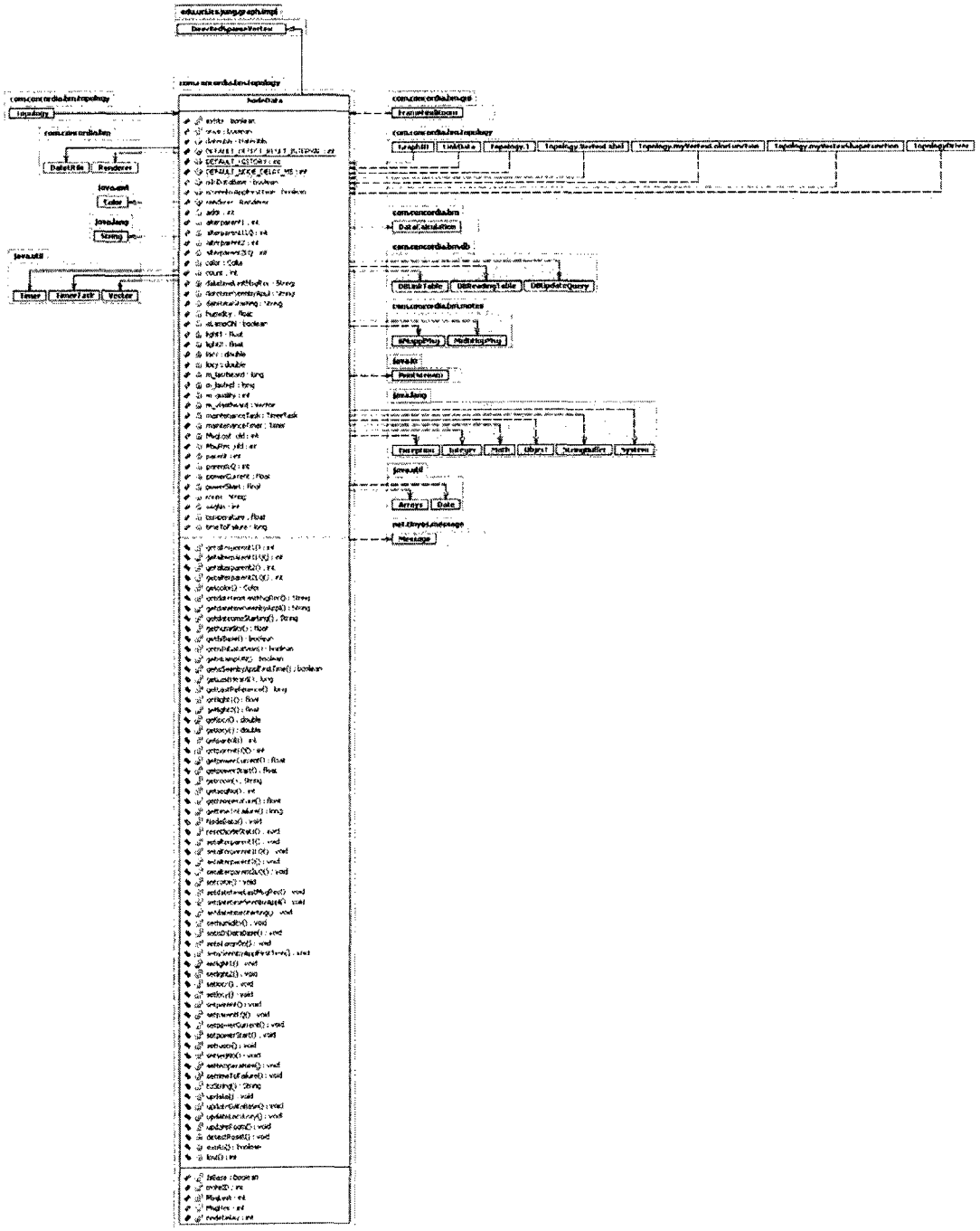


Figure 96: Class com.concordia.bm.topology.NodeData

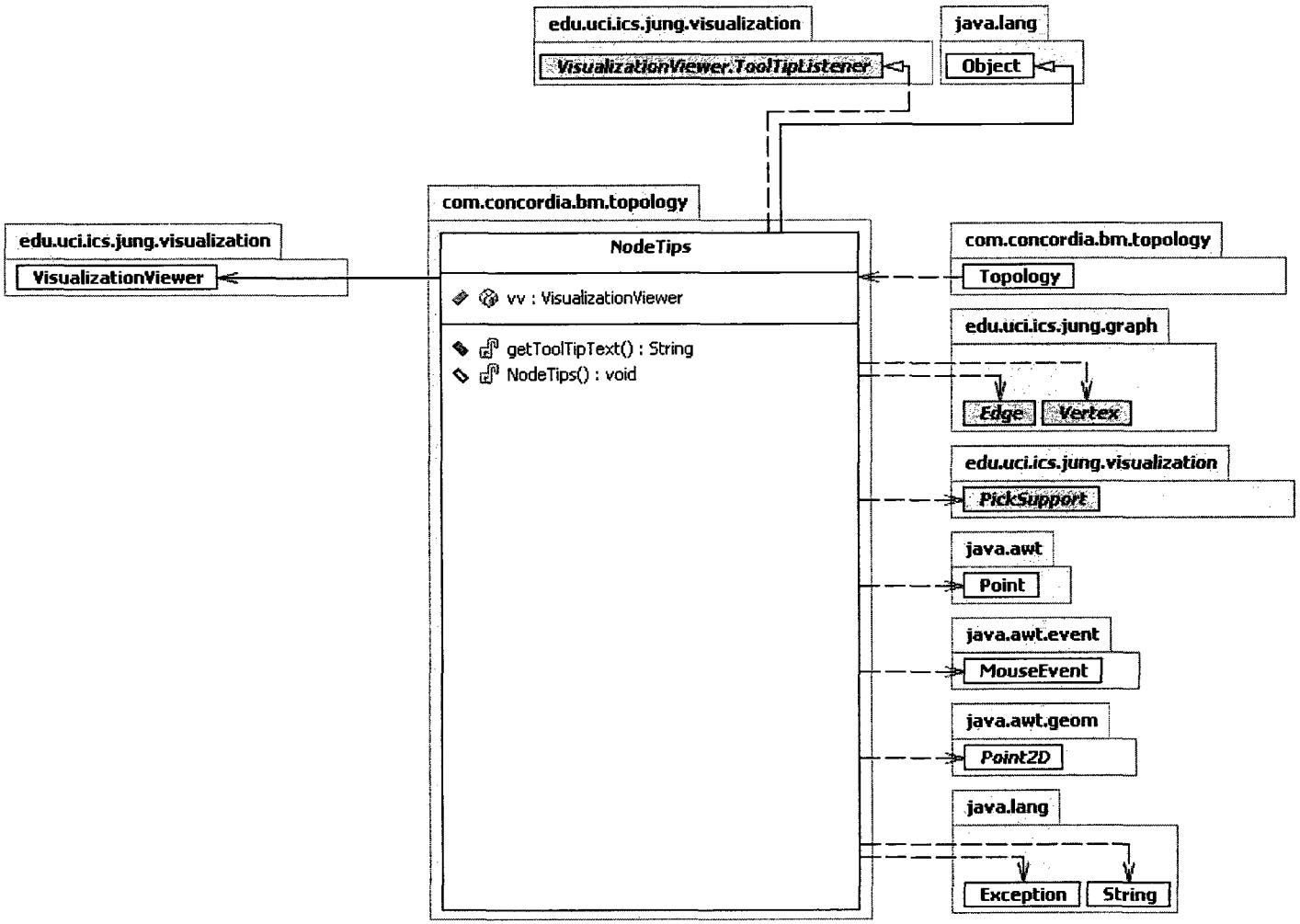


Figure 97: Class com.concordia.bm.topology.NodeTips

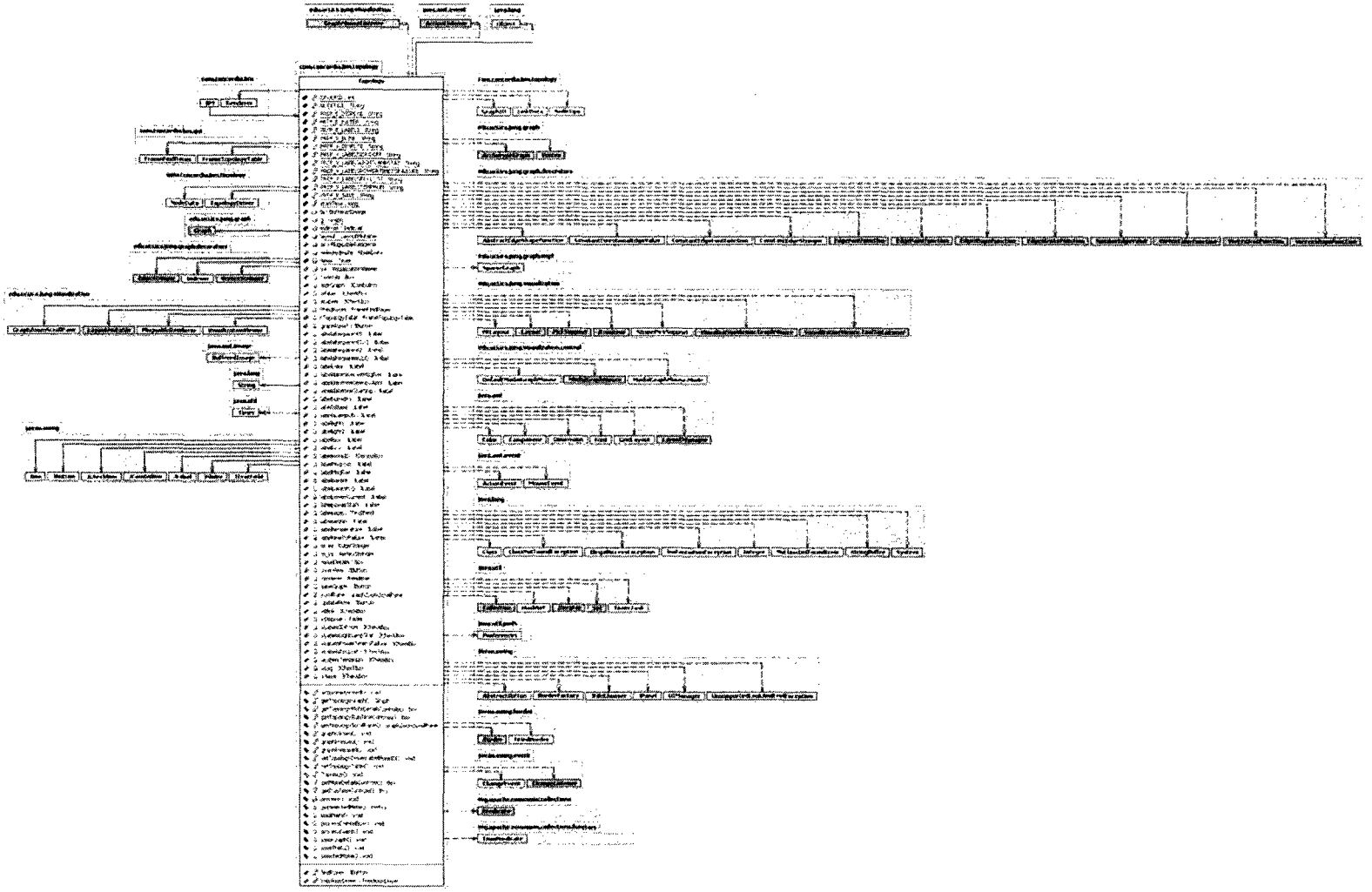


Figure 98: Class com.concordia.bm.topology.Topology

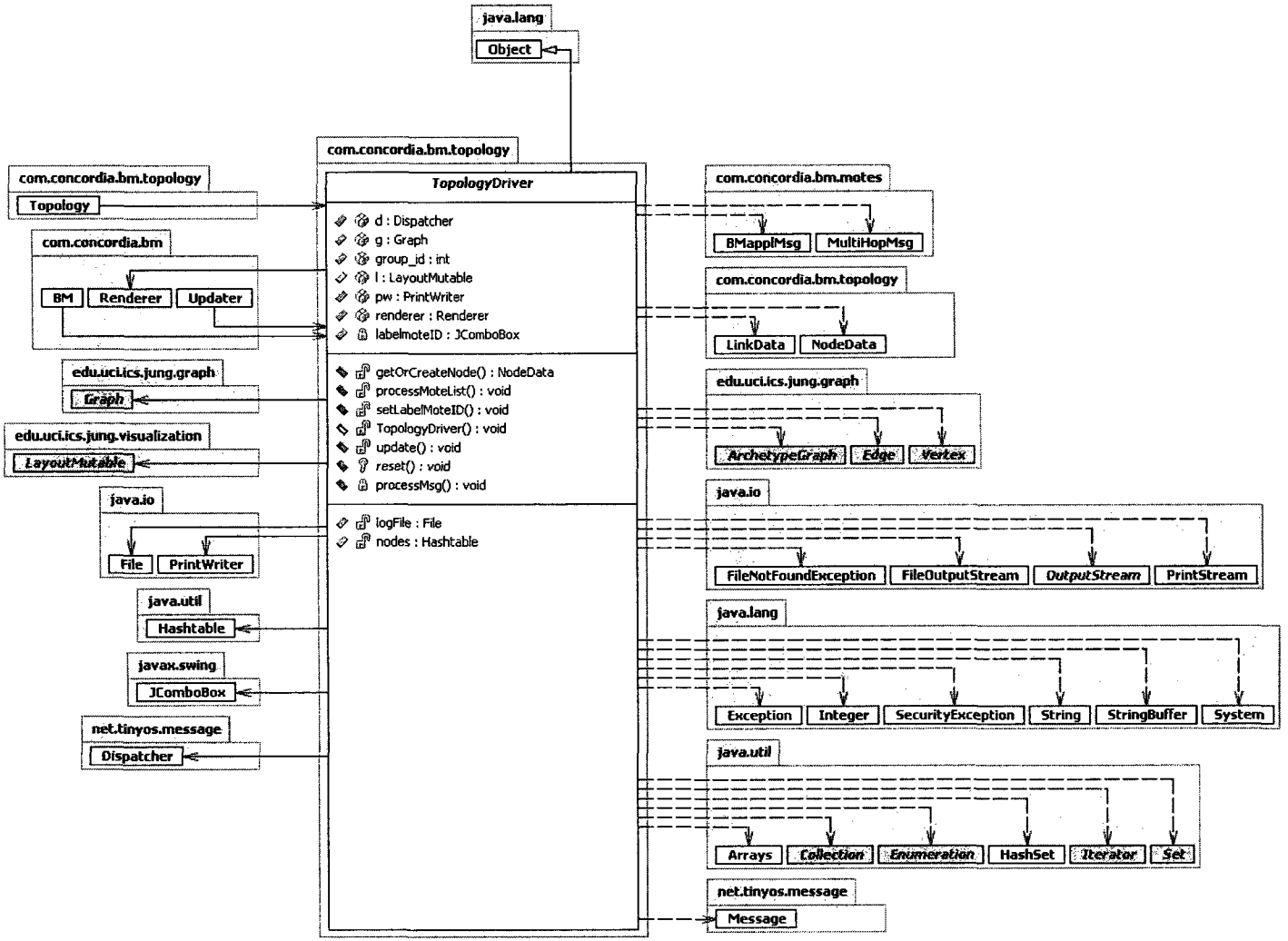


Figure 99: Class com.concordia.bm.topology.TopologyDriver

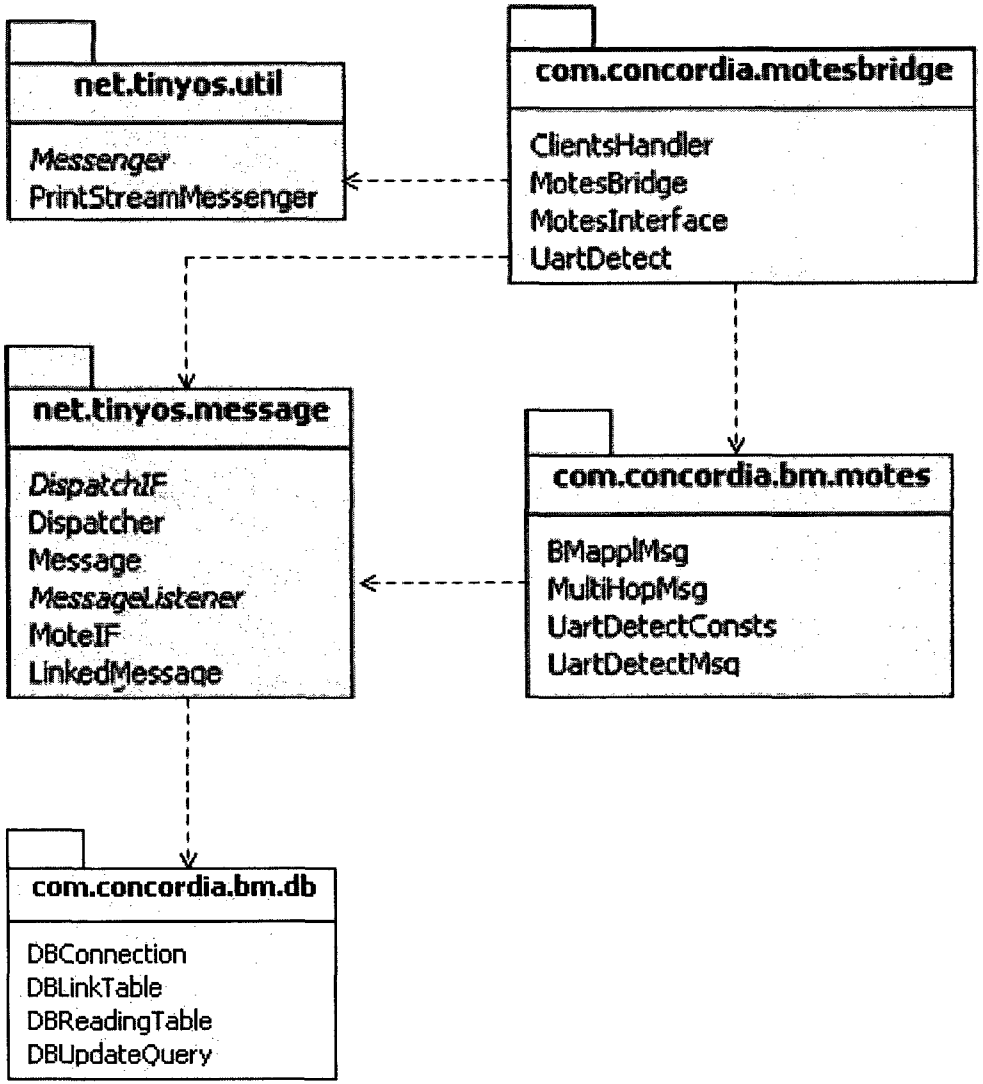


Figure 100: gateway/server

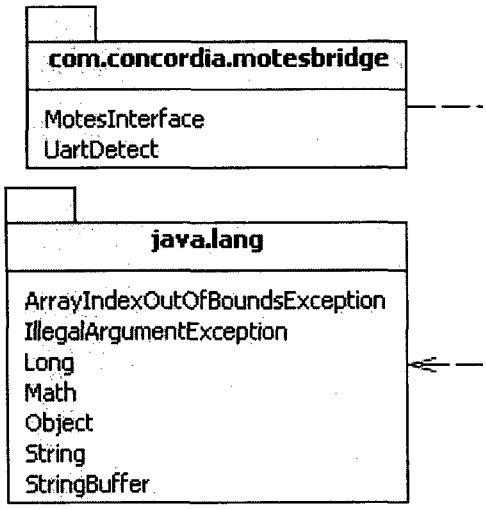
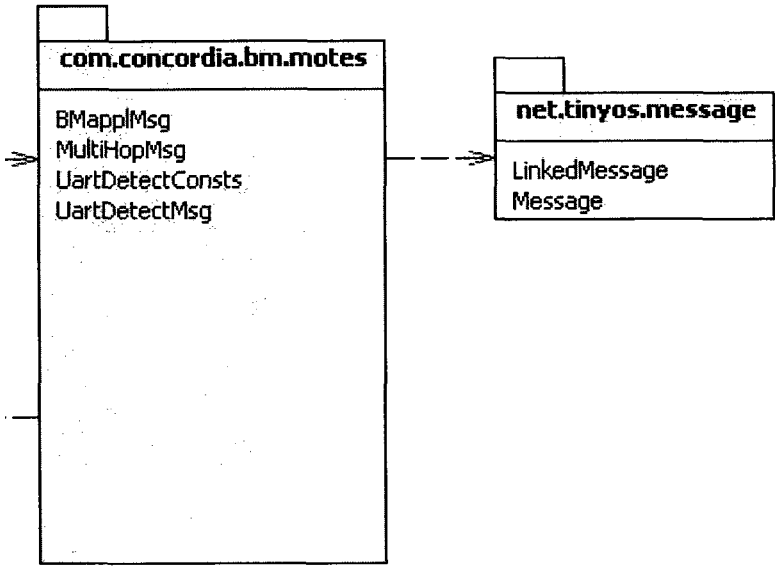

com.concordia.motesbridge
MotesInterface
UartDetect
java.lang
ArrayIndexOutOfBoundsException
IllegalArgumentException
Long
Math
Object
String
StringBuffer

Figure 101:



Package com.concordia.bm.motes

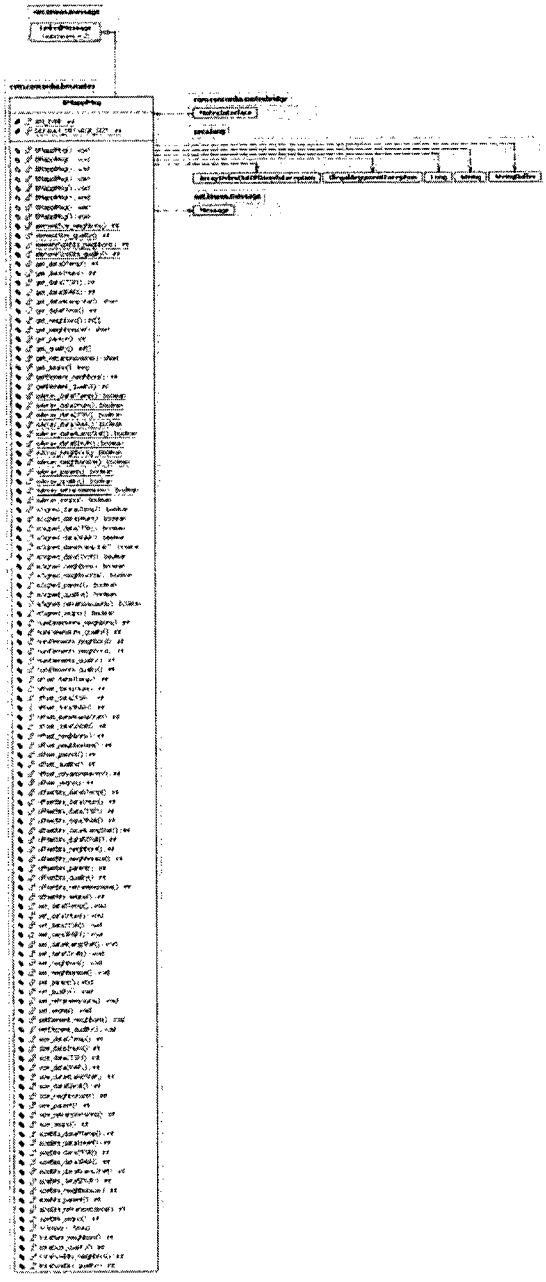


Figure 102: Class com.concordia.bm.motes.BMapplMsg

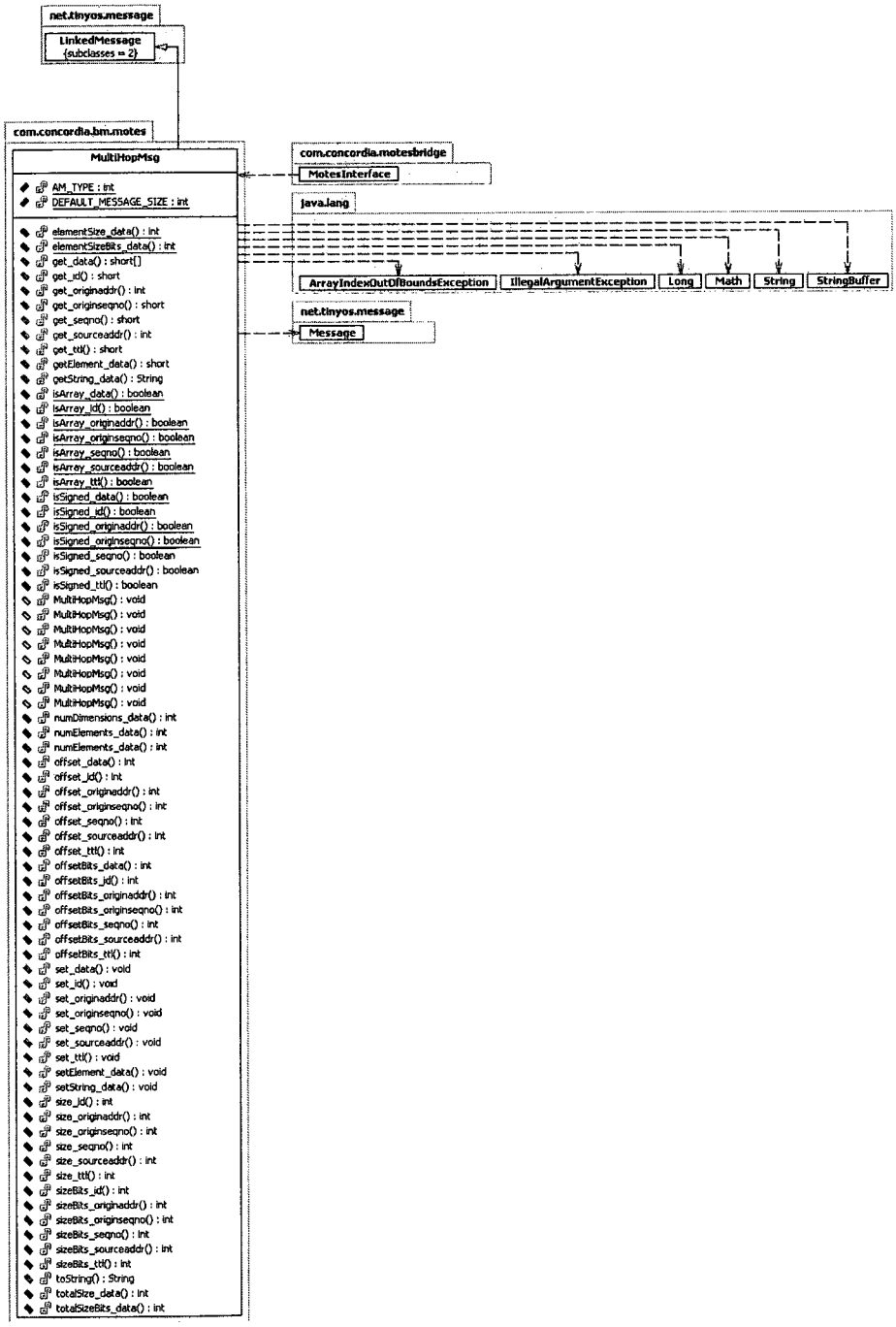


Figure 103: Class com.concordia.bm.motes.MultiHopMsg

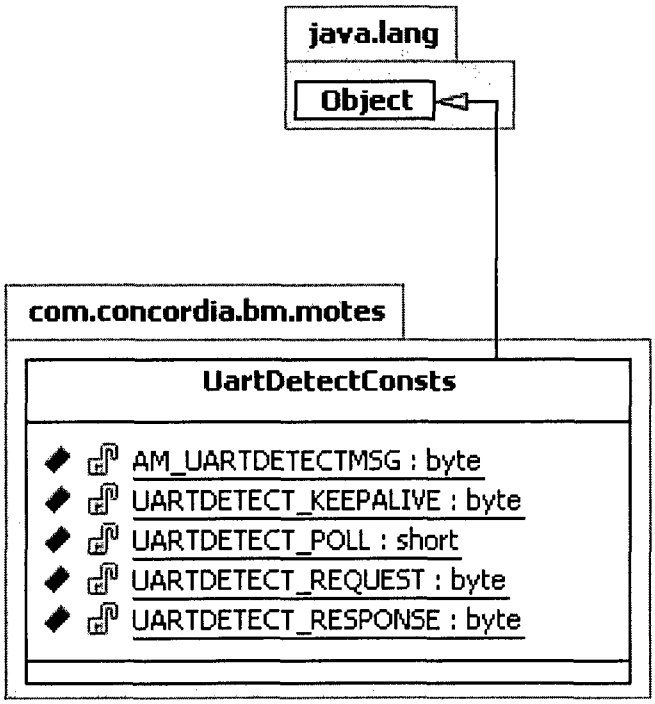


Figure 104: Class com.concordia.bm.motes.UartDetectConsts

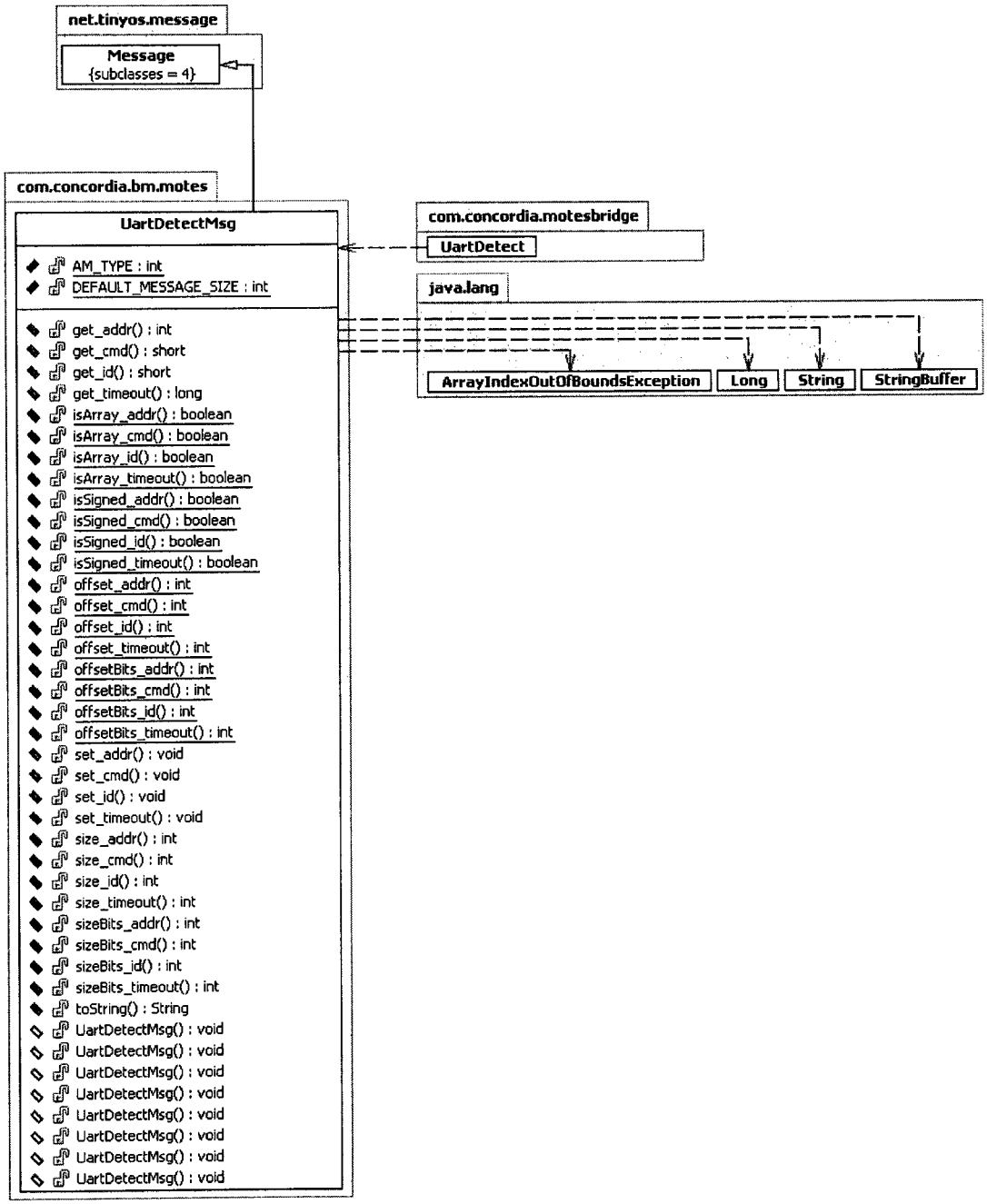


Figure 105: Class com.concordia.bm.motes.UartDetectMsg

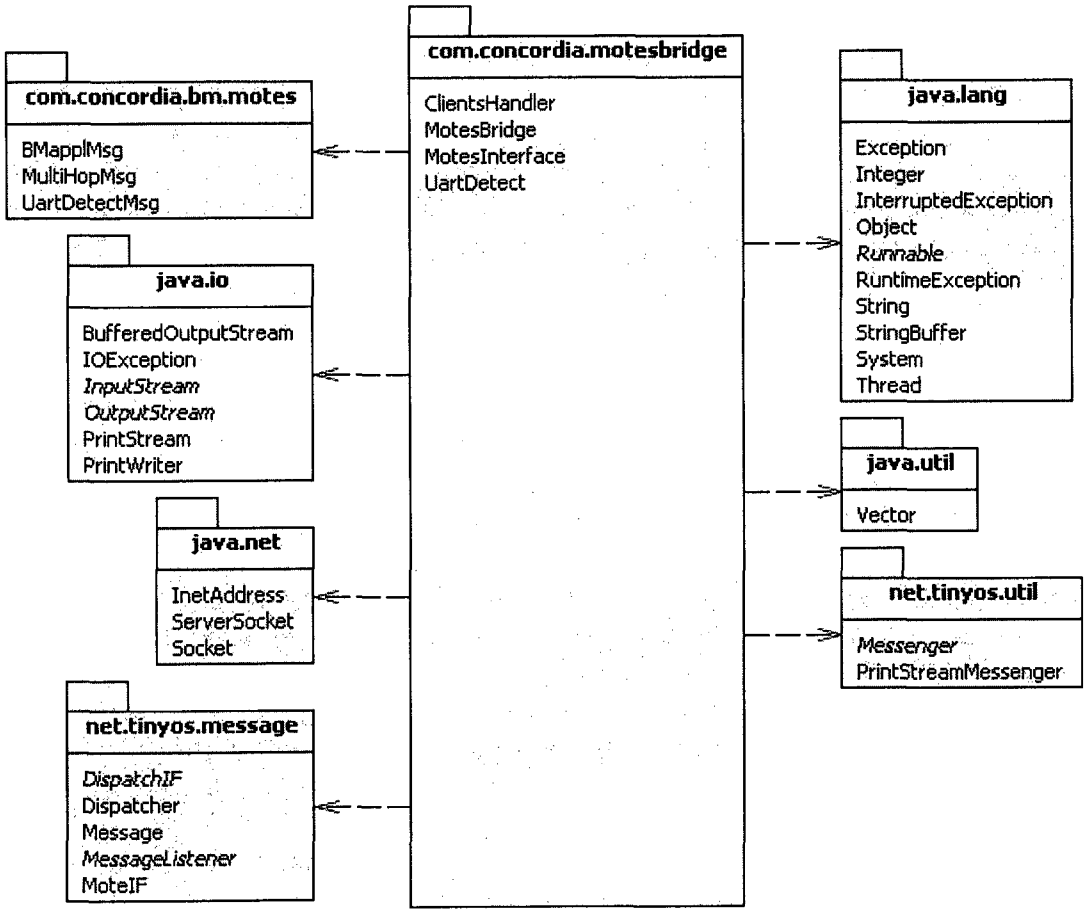


Figure 106: Package com.concordia.motesbridge

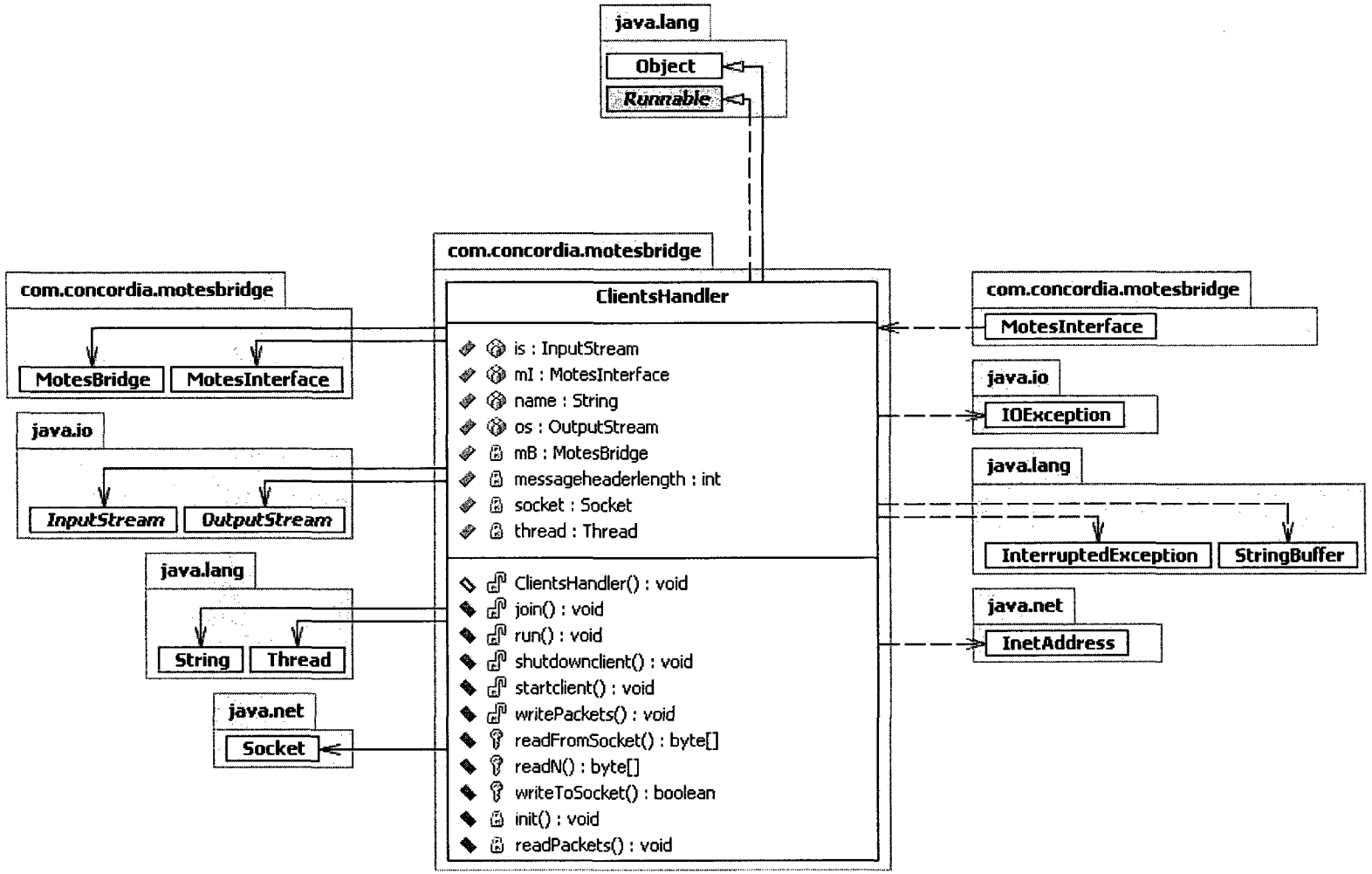


Figure 107: Class com.concordia.motesbridge.ClientsHandler

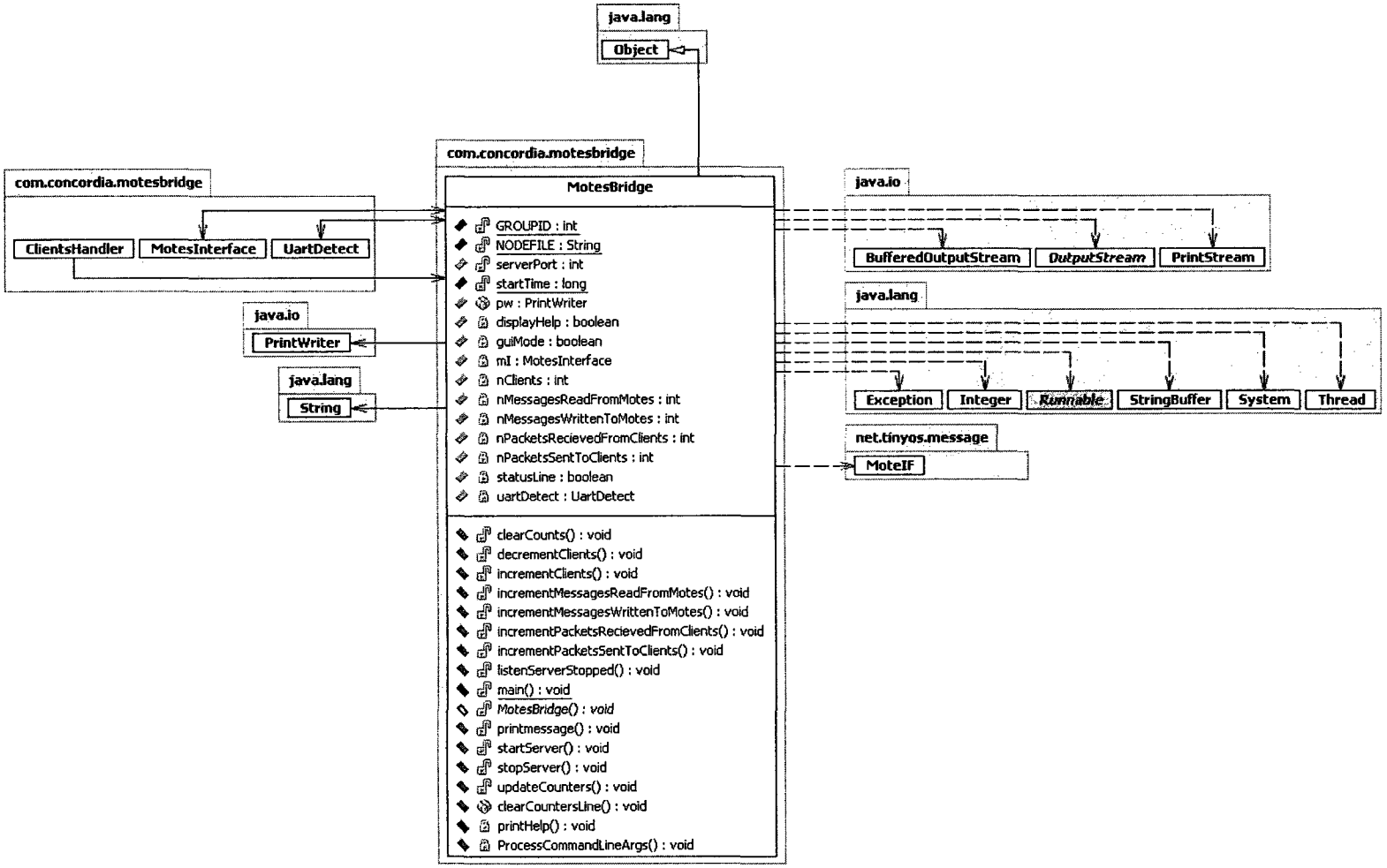


Figure 108: Class com.concordia.motesbridge.MotesBridge

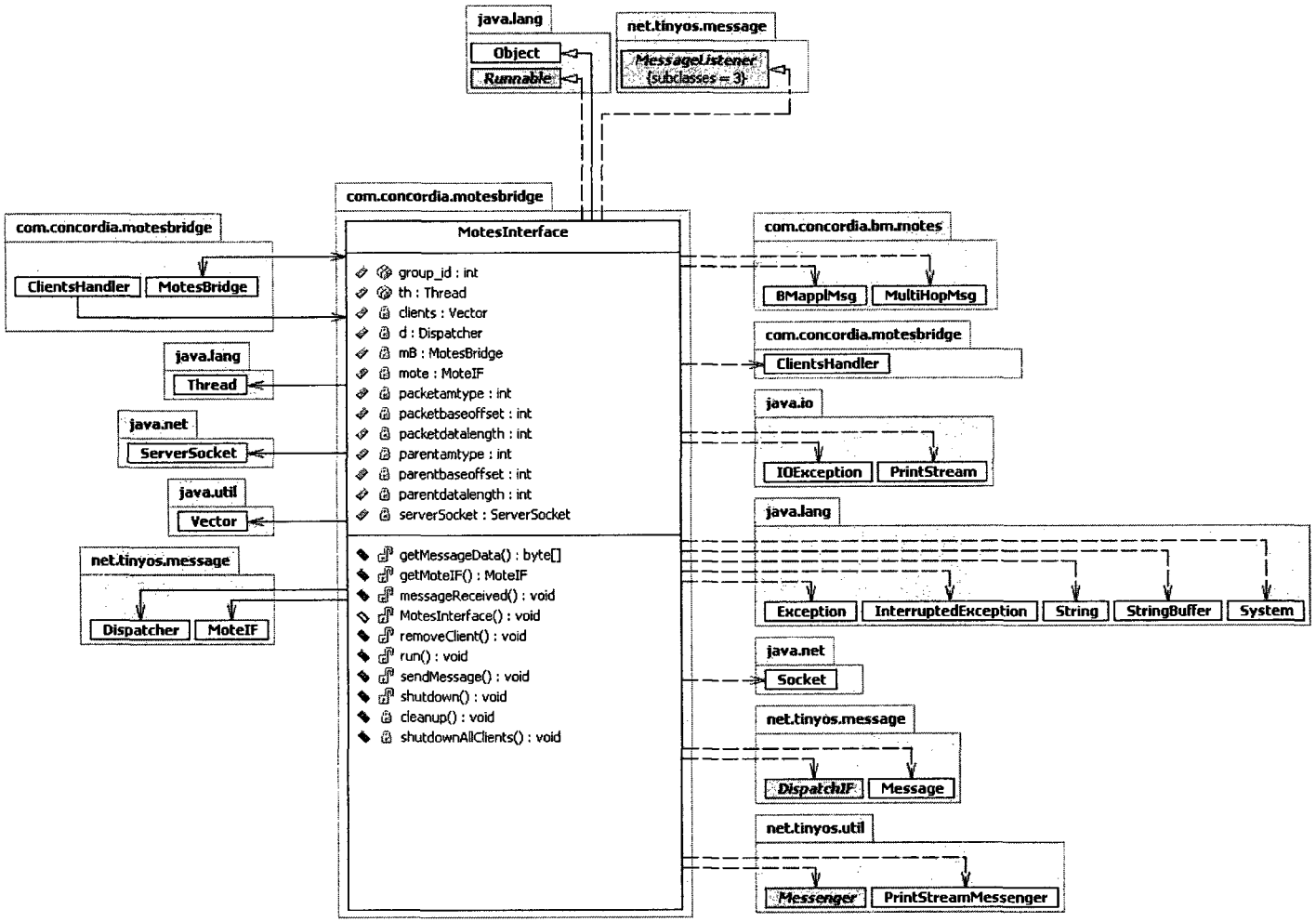


Figure 109: Class com.concordia.motesbridge.MotesInterface

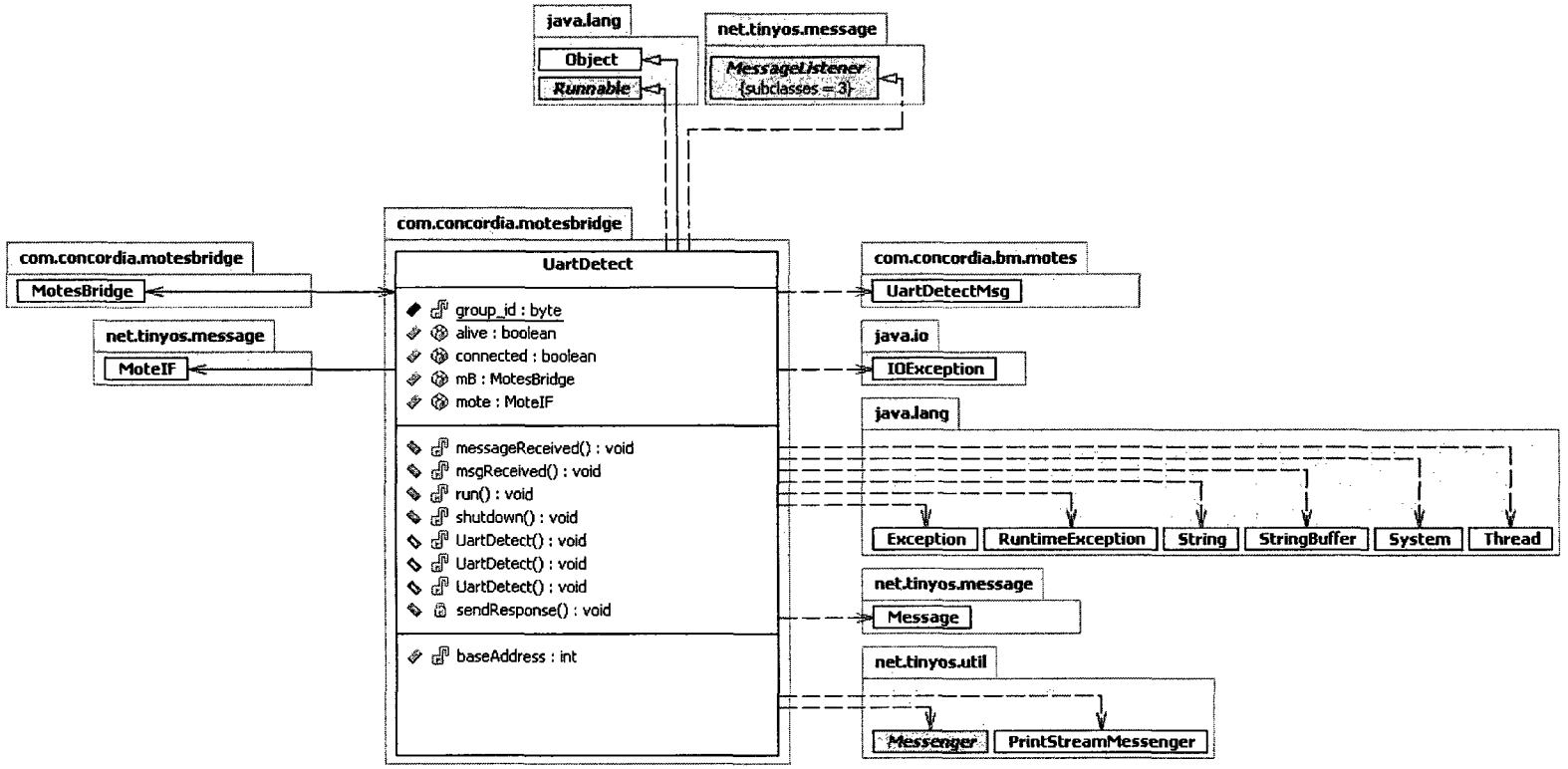


Figure 110: Class com.concordia.motesbridge.UartDetect